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Assessing the Impact of Ammonia Emissions from Mink Farming in Denmark on Human Health and Critical Load Exceedance

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Abstract

In this study, the objective is to assess the impacts of NH_3 emissions from mink farming on human health and nature, which are sensitive to atmospheric nitrogen deposition. The impact-pathway approach is applied to follow the emissions from source to impact on human health in Europe (including Denmark) and from source to critical nitrogen load exceedances for NH_3-sensitive nature in Denmark. The Danish Eulerian Hemispheric Model (DEHM) is used for modelling the air pollution concentrations in Europe and nitrogen depositions on land and water surfaces in Denmark arising from NH_3 emissions from mink farming in Denmark. The Economic Valuation of Air (EVA) pollution model system is applied for deriving the health effects and corresponding socio-economic costs in Denmark and Europe arising from the emissions from mink farming. On a local scale in Denmark, the deposition resulting from the NH_3 emissions from mink farming is modelled using the results from the OML-DEP model at a high resolution to derive the critical nitrogen load exceedances for Danish nature areas sensitive to NH_3. From the analysis of the impacts through human exposure to the air pollutants $PM_{2.5}$, NO_2, and O_3, it is concluded that in total, ~60 premature deaths annually in Europe, including Denmark, can be attributed to the emissions of NH_3 to the atmosphere from the mink farming sector in Denmark. This corresponds to annual socio-economic costs on the order of EUR 142 million. From the analysis of critical load exceedances, it is concluded that an exceedance of the critical load of nitrogen deposition of ~14,600 hectares (ha) of NH_3-sensitive nature areas in Denmark can be attributed to NH_3 emissions from mink farming. The cost for restoring nature areas of this size, damaged by eutrophication from excess nitrogen deposition, is estimated to be ~EUR 110 million. In 2020, the mink sector in Denmark was shut down in connection with the COVID-19 pandemic. All mink were culled by order of the Danish Government, and now in 2025, the process of determining the level of financial compensation to the farmers is still ongoing. The socio-economic costs following the impacts on human health in Europe and nitrogen-sensitive nature in Denmark of NH_3 emissions from the now non-existing mink sector can therefore be viewed as socio-economic benefits. In this study, these benefits are compared with the expected level of compensation from the Danish Government to the mink farmers, and the conclusion is that the compensation to the mink farmers breaks even with the benefits from reduced NH_3 emissions over a timescale of ~20 years.

Keywords: ammonia emissions; mink farming; health impacts; critical load exceedance; nitrogen deposition

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1. Introduction

On 3 November 2020, the Danish Prime Minister announced a temporary ban on mink until the end of 2021 and ordered that all mink in the fur animal sector in Denmark be culled within 14 days. The ban was later extended to the end of 2022. The reason was the fast spreading of a COVID-19 virus mutation in animals among the Danish fur farms combined with the findings of this specific mutation in infected humans. These findings were centred around nursing homes in the area of mink farms, mink farm workers, and other employees of the mink industry. The Netherlands, Poland, and Ireland made similar bans on mink production. Denmark was globally the largest producer of mink furs with world leading qualities. In 1990, around 10 million mink furs were produced, increasing to 18 million mink furs in 2017 [1] out of a global production of app. 66 million mink and fox pelts in 2019 [2]. Denmark also included the world's largest fur auction house, Kopenhagen Fur (https://www.kopenhagenfur.dk, accessed on 11 November 2021). In Denmark, as a result of the ban, a total of 17 million mink were culled within a short time period, and a governmental process to financially compensate the affected mink farmers started. In 2025, this process is still ongoing.

Before the COVID-19 pandemic, Denmark, the Netherlands, Finland, and Poland were the countries in Europe with the most mink farms. Mainly due to animal welfare concerns, several European countries (Austria, Belgium, Croatia, Czechia, Luxembourg, North Macedonia, Serbia, Slovenia, Switzerland, and the UK) had for some years banned fur farming. More recently, and after the pandemic, a number of countries are planning bans or have decided on a phase-out period (these include the Netherlands, France, Ireland, Slovakia, Norway, Belgium (Flanders), Germany, Bosnia, and Herzegovina) [3]. In 2023, the global production was estimated to be only 15 million mink and fox pelts [2].

Mink are carnivores, the production of mink smells, and it attracts flies. The Danish success with mink fur production relies on skilled farmers and their ability to systematise the sale, combined with access to large quantities of feed and relatively small areas of open land where the mink production can be located. The food for mink is mainly leftovers from the large Danish fishing industry, and mink production is therefore typically found near the large fishing harbours in the western part of Denmark. Good agricultural soil is not necessary to produce mink fur, and so the production historically originated among the poorest farmers/farm workers, which coincided with those owning or working on limited land with nutrient-poor sandy soils, which are typical for the western part of the country.

Sensitive nature areas are typically also characterised by nutrient-poor soils, and a strong correlation between the location of sensitive nature areas and mink fur farms is therefore found in Denmark. In 2019, the mink farming sector was responsible for 7.3% of the agricultural ammonia (NH_3) emissions in Denmark. NH_3 contributes to the atmospheric concentration and deposition of *reactive nitrogen* (Nr) to ecosystems, and loss of biodiversity in terrestrial ecosystems has been shown to be a direct consequence of elevated Nr deposition from the atmosphere [4–6]. Emissions contributing to atmospheric Nr deposition are regulated using the *critical load* (CL) approach, where nature areas are protected according to the critical load of Nr deposition for the specific nature type [7–9]. However, exceedances of the critical loads are still widespread for terrestrial ecosystems in Europe, and Denmark is one of the most affected areas [9]. Accumulated consequences of Nr deposition are seen in many terrestrial ecosystems, where species richness is declining in Europe [10–12] as well as outside of Europe [13,14]. Similar results have been observed in the Danish monitoring programme for water and nature.

Human health is impacted by air pollution, especially by the concentration of *fine particulate matter* ($PM_{2.5}$) in the air [15,16]. The evaluation of impacts and socio-economic costs as well as how reductions in ambient air pollution concentrations benefit society are emerging research topics [17–20]. NH_3 contributes to $PM_{2.5}$ in the atmosphere through chemical reactions with nitric acid and sulfuric acid to form ammonium-nitrate and ammonium-sulphates. The agricultural emissions therefore also play a role in human health impacts. Calculations within the Danish national air quality monitoring programme have shown that 27% of the total socio-economic costs in Denmark related to health impacts from all emissions of air pollution in 2023 arose from Danish emissions of NH_3, which is mainly attributed to agricultural activities [21].

Other studies have examined the environmental impact of mink farming, primarily with a focus on aquatic eutrophication from run-off [22], environmental contamination with heavy metals and persistent organic compounds [22,23], the transmission of viruses, such as COVID-19, to other animals and humans [24], and mink as an invasive species in nature [22,25]. Studies focusing on how air pollution from mink farming specifically impacts human health and atmospheric Nr deposition have not been found, while more general studies of how agricultural activities lead to negative impacts can be found. A mini-review by de Vries [6] summarises how the loss of reactive nitrogen leads to adverse impacts on terrestrial ecosystems (e.g., plant species loss), aquatic ecosystems (algal blooms, plant species loss), and human health through both PM formation and the pollution of drinking water. The impacts on human health are described in more detail in the review by Wyer et al. 2022 [26], where both the direct effects of NH_3 (mainly on the respiratory system) and the contribution of $PM_{2.5}$ exposure, and hence chronic health problems leading to premature mortality, can be directly linked to NH_3 emissions from agriculture.

On this background, the focus of this study is to assess the impact on sensitive ecosystems in Denmark and human health in Europe, including Denmark, from the reduction in NH_3 emissions following the ban on mink farming in Denmark. It is also the aim to estimate the corresponding socio-economic costs and potential benefits. It is hypothesised that there are substantial socio-economic benefits from the reduction in NH_3 emissions when mink farming is banned. It is also hypothesised that these benefits could be comparable in size to the governmental compensation costs of closing the entire national mink industry.

2. Methods and Data

In the evaluation of the environmental impacts of the Danish mink farming sector presented in this study, the focus is solely on the changes in emission of NH_3 from the point sources (houses and manure storage) corresponding to the locations of the farms in 2019. Data detailing point source emissions are well reported in the Danish system and can be directly included in the modelling study. Additional emissions will take place from the application of the manure from mink farms on agricultural fields; however, the data on field applications of manure are not available and have therefore not been included in the model calculations. Data on the housing location of all agriculture-related animals including fur animals have been recorded since 1996, and from 2010, the information also includes housing type [27,28]. The annual NH_3 emissions from housing and manure stores are based on the Danish Normative System [29]. The Danish Normative System is the annually updated normative nitrogen excretion rates for all agricultural animals, including correction factors for differences in productivity on each farm (nitrogen feeding strategy, milk production, number of piglets, number of cubs, etc.) and the related NH_3 emission for each housing system.

The flow of NH_3, from emission to the atmosphere to effects in humans and the environment, is depicted in Figure 1. In this study, we consider the chemical transformations of NH_3 resulting in airborne $PM_{2.5}$ and the contribution from NH_3 and reaction products of NH_3 to the dry and wet deposition of Nr.

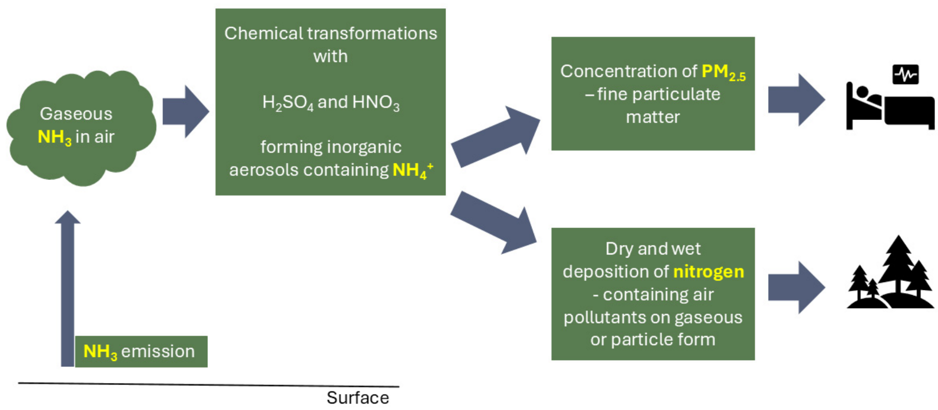

Figure 1. Flow of NH_3 from emissions from sources to gaseous NH_3 in air, where the gas will be transported with the wind and either react with sulfuric acid (H_2SO_4) or nitric acid (HNO_3) to form inorganic aerosols that contain NH_4^+ or deposit on the surface. NH_4^+ contributes to the ambient concentration of fine particulate matter, which affects human health, and NH_3 and NH_4^+ both contribute to the dry and wet deposition of Nr.

To quantify the impacts, a combination of air pollution modelling and impact assessment has been used. The modelling is performed with the regional-scale chemistry-transport model DEHM (Danish Eulerian Hemispheric Model) and a local downscaling technique for the NH_3 deposition based on high-resolution proxies from the OML-DEP model. The impact assessment is performed with the EVA (Economic Valuation of Air pollution) model system for human health impacts and costs. All methodologies and data are described in the following.

2.1. Regional Scale Modelling

The Danish Eulerian Hemispheric Model (DEHM; [30,31]) is used to calculate the concentrations and depositions of all relevant air pollution components (80 in total, including the components NH_3 and $PM_{2.5}$) for the whole of Denmark. All relevant reaction products and reactants related to the emissions of NH_3 from mink farming are included. Both organic as well as inorganic chemical reactions are included in the model. The inorganic reactions describe the transformation and reactions of the different Nr components. Included in the calculated depositions from the DEHM are the gaseous Nr components NH_3, nitric acid (HNO_3), nitrogen-oxides (NO and NO_2), dinitrogen-pentoxide (N_2O_5), and peroxy-nitric-acid (HO_2NO_2) and the particulate components ammonium-nitrate (NH_4NO_3), ammonium-bisulphate (NH_4HSO_4), ammonium-sulphate ($(NH_4)_2SO_4$), peroxy-acetyl-nitrate (PAN) and organically bound nitrates. Some of these components are in the gas phase (e.g., NH_3), others in the particle phase (e.g., reaction products from NH_3), and both gas phase reactions and gas-to-particle conversions are taken into account. All the particulate components resulting from NH_3 also contribute to the mass concentration of $PM_{2.5}$.

The domain of the DEHM covers the Northern Hemisphere in a polar stereographic projection true at 60° N, with a spatial resolution of 150 km × 150 km. High resolution is obtained over the Danish area using a two-way nesting technique, increasing the resolution over Europe (to 50 km × 50 km), Northern Europe/Scandinavia (to 16.67 km × 16.67 km), and Denmark (to 5.56 km × 5.56 km). In the vertical, 29 model levels resolve the lowest app. 15 km of the atmosphere.

The DEHM is part of the Copernicus Atmospheric Monitoring Service, which provides ensemble-based operational daily air quality forecasts for Europe (https://atmosphere.copernicus.eu/, accessed on 3 January 2024). The calculated concentrations and depositions of the DEHM are evaluated in [32,33] and on a routine basis in the Danish monitoring programme for water and nature (NOVANA; e.g., [34]).

Setup of the DEHM

Meteorological data calculated with the Weather Research and Forecasting model version 3 (WRF, [35]) are used as input for the DEHM. The WRF model is setup with the same domain and horizontal resolution as the DEHM to avoid interpolation in space, and hourly output is saved to minimise errors from interpolation in time. Land cover data are based on the EMEP classification [36]. Anthropogenic emission data for the hemisphere are based on the Eclipse v6b database [37] and for Europe on the EMEP database [38].

For Denmark, the emissions from the national emission model SPREAD [39] with 1 km $\times$ 1 km resolution are included in the calculations. These data are supplemented with very-high-resolution emission data for NH_3 from the agricultural sector, further described below. Natural emissions are derived from the Global Emissions InitiAtive dataset (GEIA, [40]) or are calculated directly in the DEHM (see [41,42]). All anthropogenic emissions are provided as gridded annual totals and redistributed over the year for individual countries, emission sectors, and chemical components using standard monthly temporal profiles. The temporal variation across the week and the day also depends on the sector and chemical component but is averaged across the whole of Europe. All temporal profiles are obtained from the EURODELTA project [43]. Dynamic temporal time profiles are included for the Danish NH_3 emissions taking agricultural practice and meteorology into account [44,45].

Meteorology is an important factor for air pollution, and to reduce the influence of meteorological variations on the resulting concentrations and depositions, the model runs are performed for the meteorological years 2017, 2018, and 2019, with emissions from 2019. The DEHM provides the possibility for following—or *tagging*—emissions from a specific sector, country, or individual source. The methodology is documented in [46].

NH_3 emissions from mink farming in Denmark are tagged in the model runs with the DEHM, and the atmospheric concentrations and depositions, here denoted *delta-concentrations* and *delta-depositions*, of the chemical pollutants directly related to the emissions of NH_3 from mink are analysed separately. The delta-concentrations are used as input for the impact assessment for human health, and the delta-depositions of NH_3 (together with the other components that contribute to Nr) are used as input for the assessment of critical load exceedances. Both assessment methodologies are described below.

The NH_3 emissions from mink farming are based on the national inventory of all farm animals, from which the emissions of the individual mink farms have been extracted. The specific location is only known for the point sources (housing and manure stores), whereas the locations of the area sources (the agricultural fields where the manure from the mink farms are applied) are unknown in the system. Figure 2 shows the distribution (location and number) of female mink in Denmark. As described in the introduction, the concentration of mink farms is most dense in the western part of Denmark, where sandy soils dominate over clay. This is clearly seen in the distribution of female mink in Figure 2.

2.2. Human Health Impact Assessment

The Economic Valuation of Air pollution model system (EVA; [46,47]) is based on the impact-pathway chain [48]. This is a method used for understanding the impacts from specific emission sources or source sectors, by following the emissions in atmospheric transformation and transport to exposure and the final impact, e.g., on human health. The EVA system makes it possible to assess the health effects and related societal costs/benefits of air pollution from specific emission groupings/scenarios, e.g., in sectors, countries, or otherwise.

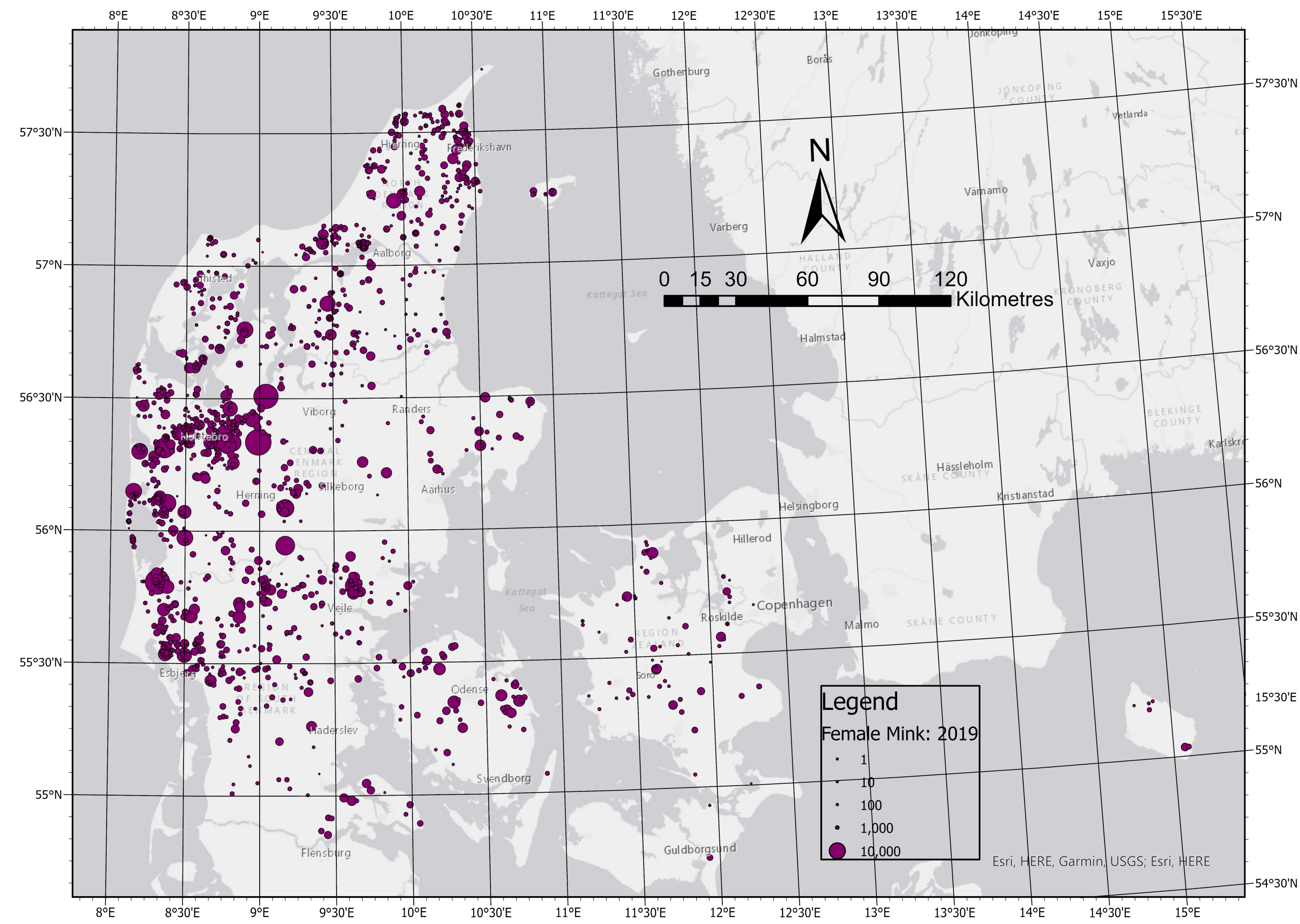

Figure 2. Location and number of female mink in Denmark. Data are obtained from the Danish Central Husbandry Register for 2019 [27].

The EVA system is based on the combination of modelled air pollution concentrations, gridded population data, exposure–response functions connecting exposure to air pollution with health outcomes, and cost estimates per single outcome. In this study, the EVAv8 setup is applied, and the modelled air pollution delta-concentrations are obtained from the DEHM as described above. The population data are based on a 2017 distribution from the national Central Person Registry (CPR) for Denmark, scaled to 2018 and 2019 with the annual national totals. For the rest of Europe, the global population density data have been combined with a dataset for country-specific age distributions and interpolated to the years 2017, 2018, and 2019 [41]. The choice of relevant air pollutants and the implementation of exposure–response functions detailing the relationship between exposure to air pollutants and health effects are based on the meta-reviews and recommendations of the WHO global air quality guidelines [16,49]. Monetary valuations are derived from [50]. Table 1 presents the included health outcomes and corresponding cost functions.

The most important air pollution components for human health impacts are $PM_{2.5}$, nitrogen dioxide (NO_2), and ozone (O_3). The delta-concentrations of these three components (and the now—due to a large decline in concentrations—less important component sulphur dioxide, SO_2) are here extracted from the results of the tagged model runs with the DEHM. In this way, the delta-concentrations reflect the emissions of NH_3 from mink farming point sources. Following the extraction, the delta-concentrations are processed with the EVA system to estimate the impact on human health.

Table 1. Health outcomes, related air pollutants, and valuation applied in the EVAv8 calculations (2022 prizes).

Health Effect (Response)	Relevant Air Pollution Components	Valuation
Mortality		
Premature deaths, short-term exposure	$PM_{2.5}$, SO_2, NO_2, O_3	EUR 4,903,877/case
Premature deaths, long-term exposure	$PM_{2.5}$, NO_2, O_3	EUR 4,167,143/YOLL *
Morbidity		
Respiratory hospital admissions	$PM_{2.5}$, NO_2, O_3	EUR 9260/case
Cardiovascular hospital admissions	$PM_{2.5}$, O_3	EUR 15,513/case
Cough	$PM_{2.5}$	EUR 1418/case
Bronchitis	$PM_{2.5}$	EUR 49,521/case
Work loss days	$PM_{2.5}$	EUR 318/case
Restricted activity days	$PM_{2.5}$	EUR 180/case
Minor restricted activity days	O_3	EUR 100/case
Lung cancer	$PM_{2.5}$	EUR 74,804/case

* Corresponding to Years Of Life Lost (YOLL).

2.3. Local-Scale Deposition of Nitrogen

The distribution of air pollution concentrations, arising from emissions from mink farming and calculated with the DEHM, are available at a 5.56 km × 5.56 km spatial resolution, which is suitable for the calculation of premature mortality and morbidity in the EVA system. However, the spatial resolution of the nitrogen deposition estimates (and therefore the delta-depositions) is too coarse for a detailed assessment of the critical load exceedances of Nr in Denmark. This is because only a few Danish nature areas, sensitive to Nr, are comparable in size to these 5.56 km × 5.56 km grid squares. Additionally, the contribution to the deposition in nature areas from local sources can be high and cause exceedances, even though these high values of deposition are not captured by the DEHM due to the relatively coarse resolution.

At the local scale, the most important component to the model is NH_3, as this component has a relatively high activity rate. It either deposits close to the source or is transported farther away by the wind, where the NH_3 either can be transformed to ammonium (NH_4^+)-forming particles, wet deposited due to rain or snow, or dry deposited. The chemical transformation and wet deposition processes are handled in the DEHM, but for the local-scale NH_3 dry deposition, a different approach is used to complement the results of the DEHM.

Based on the same farm-level NH_3 emission inventory for the point sources of mink farming in Denmark, NH_3 dry deposition is calculated on a 50 m × 50 m grid covering Denmark, using dry deposition functions for NH_3. The resulting high-resolution dry depositions of NH_3 are added to the DEHM background depositions (mean of 2017–2019) of all the other components included in Nr depositions. Finally, the total high resolution Nr deposition map is compared with national critical load limits for Nr and detailed land use data for Denmark to assess the impact of changes in Nr deposition to sensitive nature areas with respect to where critical loads are exceeded.

The dry deposition functions have been constructed using the local-scale Gaussian plume model OML-DEP [51,52]. OML-DEP is a high-resolution dispersion model specifically developed for the local-scale deposition of ammonia and part of the Danish Ammonia MOdelling System (DAMOS; [33]). The DAMOS is based on a coupling between the DEHM for the regional scale and the OML-DEP model for the local scale, and the system is used, e.g., in the reporting of the deposition of NH_3 to Danish nature areas in the national monitoring programme for water and nature (NOVANA; e.g., [34]).

To construct the dry deposition functions, the OML-DEP model was run on a 4 km × 4 km domain with a horizontal resolution of 400 m × 400 m. The model was run *with* and *without* emissions of NH_3 from a point source located on the upwind edge of the domain. The difference in the calculated dry deposition between the two runs corresponds to the contribution of the specific source to the dry deposition of NH_3. The calculated dry deposition from the source is then scaled according to the emission strength of the source to provide the annual dry deposition of NH_3 corresponding to one kg of emitted NH_3. These calculations with the OML-DEP model have been repeated for a large number of combinations of source characteristics and land cover categories to reflect the variation in parameters relevant for dry deposition processes.

The resulting dry deposition of NH_3 to a nature area at distance *L* from the source can be calculated as:

$$A(L) = E \cdot D(L) \cdot \frac{VF}{100} \cdot VK$$

where *A* is the annual dry deposition of NH_3 [kg N/ha/yr], *E* is the emission from the point source, and *L* is the distance from the source. *D* is the dry deposition function derived from the OML-DEP results. It describes the standard dry deposition at distance *L* for the relevant land cover characteristics of the nature area/the surface between the point source and the nature area. *VF* is the mean wind frequency in the 30° wind sector towards the nature area (based on regional data from the Danish Meteorological Institute for the time period 1985–2004). *VK* is a tabulated wind correction, depending on the mean wind speed in the selected wind sector (derived in sensitivity studies with the OML-DEP model). Figure 3 shows an example of a deposition function, *D*. The unit for *D* is kgN/ha/year pr kgN/year emitted.

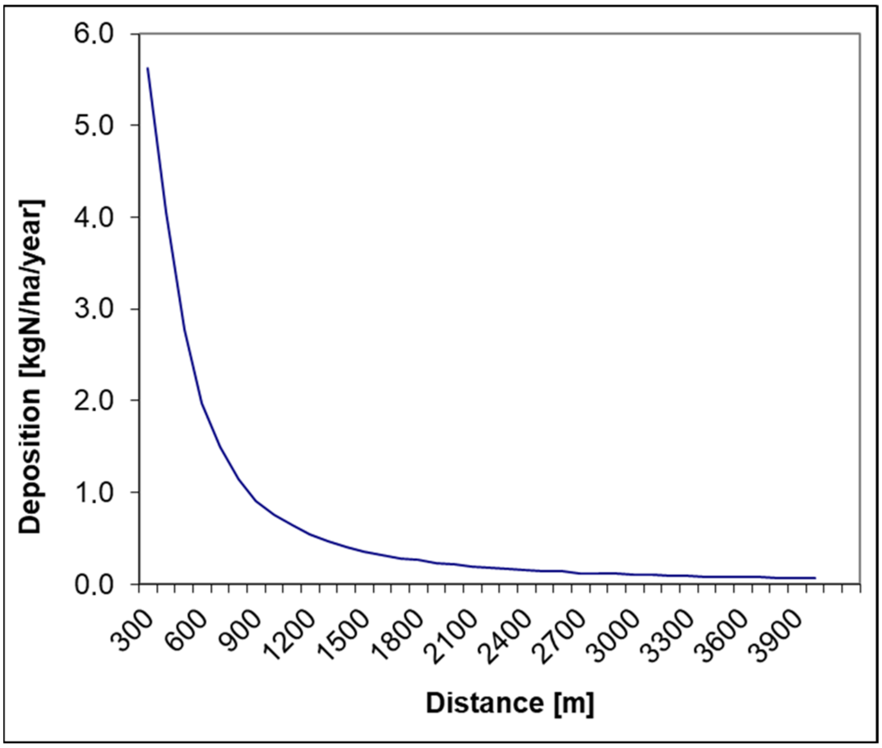

Figure 3. Annual dry deposition of NH_3 (unit kgN/ha/year) in a 30° sector with constant wind direction based on an annual point source emission of 1000 kg NH_3. Land cover characteristics in this example correspond to forest (for the nature area) and sparse vegetation (for the surface between the point source and the nature area traversed by the NH_3 emitted from the point source).

It is expected that the use of deposition curves based on twenty years of meteorological data and a spatial resolution of 50 m × 50 m for the deposition assessment is a good choice for the country-scale effect. Because of the large number of farms included (~10,000) and the limited accuracy of the precise location of the emission sources (~100 m), it is not expected that the use of more advanced dispersion models would improve the accuracy of the country-scale assessment.

In the analysis of critical load exceedances for Denmark, three nature categories (defined in the Danish ammonia regulation; BEK nr 2256 by 29/12/2000) where sensitivity to NH_3 is important, are investigated:

- Category 1: NH_3-sensitive nature types within Natura 2000 areas including heathland and dry grassland in Natura 2000 areas.
- Category 2: Selected NH_3-sensitive nature types outside Natura 2000 areas, such as heath areas larger than 10 ha, dry grassland larger than 2.5 ha, raised bogs, and lobelia lakes.
- Category 3: All NH_3-sensitive nature types outside Natura 2000 areas that are not included in Categories 1 and 2; heaths, bogs, dry grasslands and NH_3-sensitive forests.

For each of the nature types included in these categories, the number of ha where the critical load is exceeded can be computed based on the resulting local-scale gridded deposition of Nr, the extent of the nature areas, and the critical loads for the specific nature types. For nature areas included in Category 1, nationally computed critical loads based on targets for biodiversity have been used [53]. For nature areas included in Categories 2 and 3, empirical critical loads developed by the UNECE Air Convention [54] have been used.

The extent and location of the nature areas is derived from the land-cover dataset Basemap02 [55], which is based on a combination of a topographical database, management plans for state forests and defence holdings, maps of protected habitat types, Natura2000 habitat types, field parcel maps, field block maps, and cadastre maps. The conversion from vector data to raster format is based on a cell size of 10 m × 10 m [56].

3. Results

In this section, the delta-concentrations and corresponding exposure and impact assessment for human health as well as the downscaled delta-depositions and resulting critical load exceedances are presented. The concentrations modelled with the DEHM for 2017–2019 have been evaluated for Europe with all available measurements of NH_3, NH_4^+, and $PM_{2.5}$ from EBAS [57] and the Danish monitoring network [21]. The result of the evaluation is presented in the Supplementary Material, Figures S1–S4.

3.1. Health Effects and Related Socio-Economic Costs Calculated with EVA

The emissions of NH_3 from mink farming result in changes in the concentrations of a number of components through chemical transformation in the atmosphere. $PM_{2.5}$ is directly influenced through the formation of NH_4^+-containing particles from NH_3. NO_2 and O_3 are indirectly influenced (but to a much smaller extent) through the reaction between NH_3 and nitric acid, which in turn affects the concentration of NO_2 and thereby also O_3, as these components are inter-related through several chemical reactions.

The modelled concentrations of NH_3 and $PM_{2.5}$ are shown in Figure 4 as the total concentration (all emissions included) and in Figure 5 as the delta-concentrations arising from the mink sector (based on the emissions from mink farming point sources only) for the average of the years 2017, 2018, and 2019.

The ambient concentration of NH_3 is seen to have a north–south as well as an east–west gradient. The first is due to the relatively lower level of agricultural activities to the north, combined with relatively higher levels of agricultural activity in the south of Denmark. Within Denmark, the highest emissions of NH_3 from agriculture take place in the western part of the country, hence the east–west gradient. Ambient $PM_{2.5}$ concentrations are dominated by a strong north–south gradient due to the long lifetime of the fine particles in the air, combined with the large source areas in northern Germany, Poland, and The Netherlands.

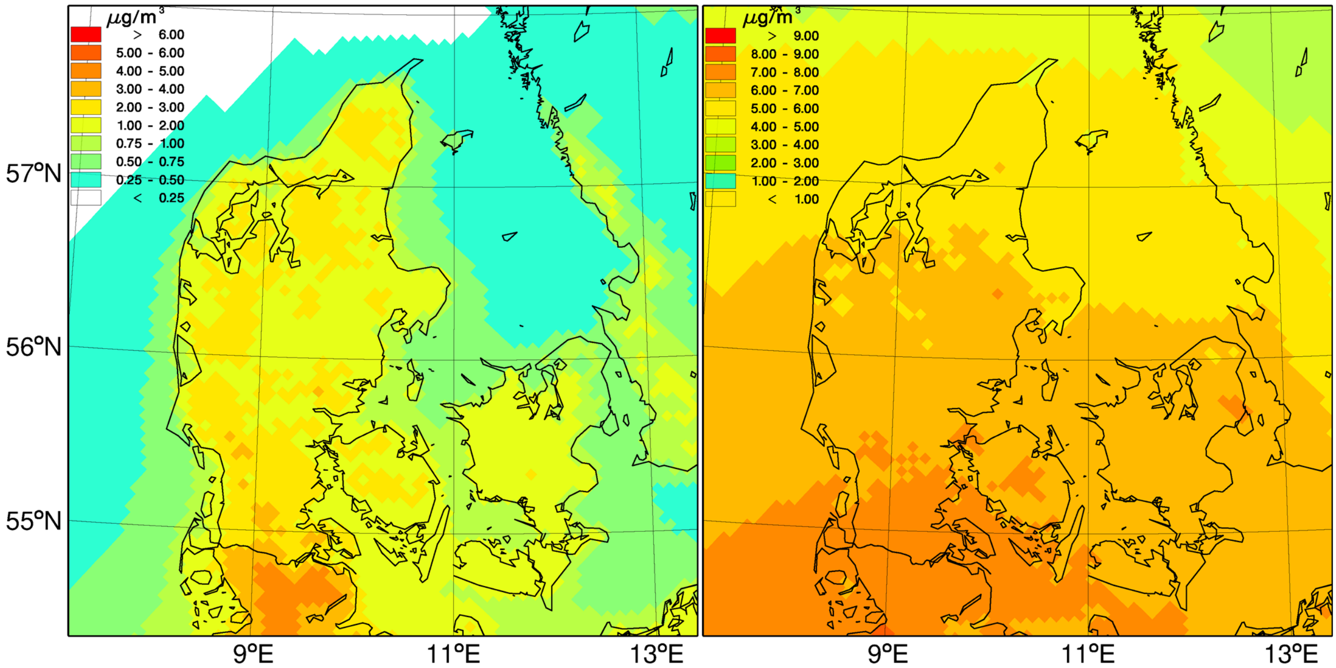

Figure 4. Average concentrations of NH_3 (**left**) in µgN/m^3 and $PM_{2.5}$ (**right**) in µg/m^3 for the time period 2017–2019 calculated with the DEHM in a setup where all emissions are included.

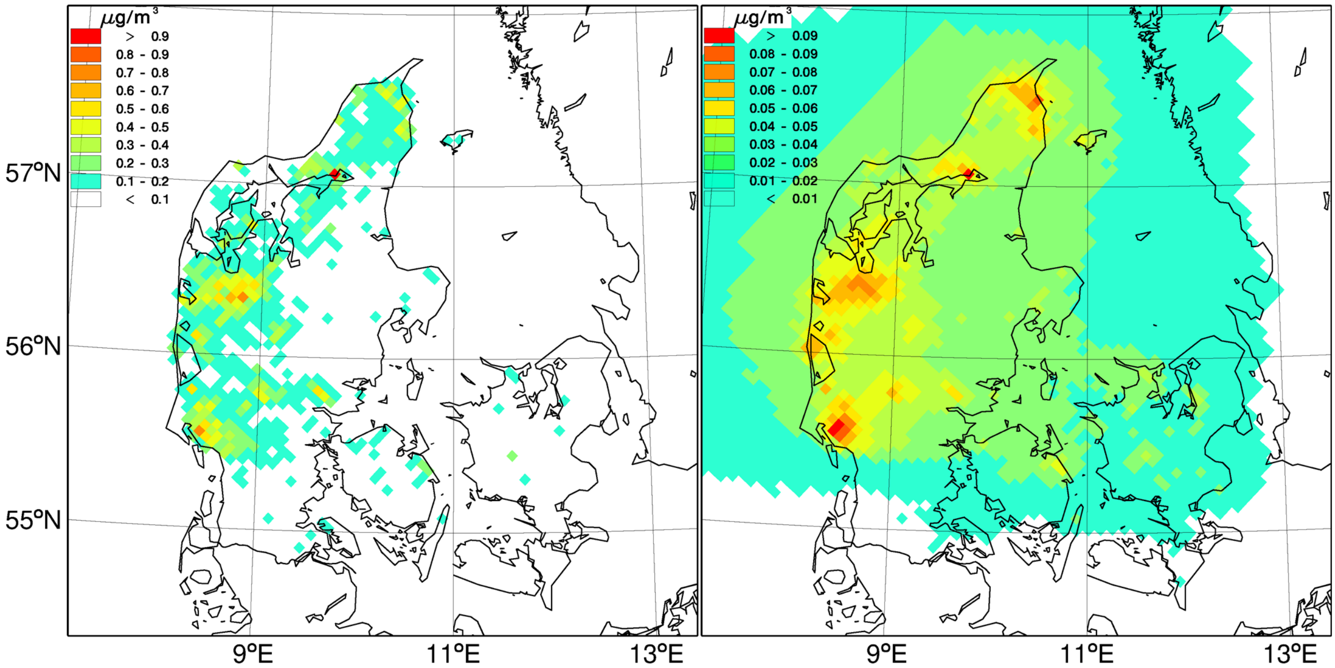

Figure 5. Average concentrations of NH_3 (**left**) in µgN/m^3 and $PM_{2.5}$ (**right**) in µg/m^3 for the time period 2017–2019 calculated with the DEHM in a setup where the contribution from the emissions from the mink sector are assessed (i.e., delta-concentrations).

Examining the delta-concentration plots in Figure 5, it can be seen that there is a strong correspondence between the location of the mink farms (Figure 2) and the concentration of NH_3 that arises from mink farm emissions. This is also the case for $PM_{2.5}$; however, the levels of the delta-concentrations of $PM_{2.5}$ are an order of magnitude smaller than the levels of NH_3, and the extent of the delta-concentration signal related to the source is larger. This can be explained by NH_3 being the primary component with by far the largest emission from the mink sector and by the shorter lifetime of NH_3 in the atmosphere compared with $PM_{2.5}$.

The annual impacts on human health for 2019 emissions are presented in Table 2. Impacts include premature deaths (mortality) and illness (morbidity) resulting from the emissions of NH_3 from mink farming, and the results are averaged over the meteorological years 2017–2019. The main cause of impacts on human health is long-term exposure to the $PM_{2.5}$ concentration in the air. In the EVA model system, the impacts can be separated between Denmark and the rest of Europe, and Table 2 presents the total impacts in Europe as a whole as well as the impacts in Denmark alone.

Table 2. Health effects (cases) and socio-economic costs (in EUR 1000) in Europe (EU) and Denmark (DK) attributed to the air pollution arising directly from emissions of NH_3 from mink farming in Denmark in 2019. All numbers represent mean values for the meteorological years 2017–2019.

Health Effect	Cases EU + DK	Cases DK	Costs (EUR 1000) EU + DK	Costs (EUR 1000) DK
Mortality				
Premature deaths, short-term exposure	5	1	23,400	4840
Premature deaths, long-term exposure	57	11	108,000	22,200
Morbidity				
Respiratory hospital admissions	23	5	214	44
Cardiovascular hospital admissions	16	3	246	51
Cough	7	1	9	2
Chronic bronchitis	197	41	2390	492
Work loss days	2850	555	906	174
Days with restricted activity	37,900	7660	6820	1370
Days with minor restricted activity	−499	−7	−50	−1
Lung cancer	8	2	577	119
Total (costs only)			142,000	29,300

In total, 64 premature deaths can be ascribed to the emissions from Danish mink farming in 2019. For Denmark alone, there are 12 cases of premature mortality. With respect to morbidity, some ~40 extra hospital admissions, ~200 extra cases of bronchitis, and ~40,000 days with work loss or restricted activity are the most prominent results. The non-linearity of the chemical reactions in the atmosphere can be seen in the results for the days with minor restricted activity. Here, the result is small but negative due to the complex chemical interactions involving NO_2 and O_3.

The annual socio-economic costs arising from these impacts on human health are also presented in Table 2. The total cost for Europe including Denmark is estimated at ~EUR 142 million annually. For Denmark alone, the cost sums up to ~EUR 29 million. It is the premature mortality that is responsible for the majority of the socio-economic costs. The results for health impacts and costs for the individual meteorological years are presented in the Supplementary Material as Tables S1–S3.

The administrative financial cost of closing the entire mink farming sector in Denmark is estimated to be DKK 24 billion (~EUR 3.2 billion). This is based on a broad political agreement regarding compensation for mink farmers [58]. With an estimated saved health cost—or benefit—per year in Denmark of ~EUR 29.3 million, it takes ~110 years before the compensation cost of closing the mink sector breaks even with the benefits from the reduction in health impacts if only the effects in Denmark are considered. If the health effects in Europe are also included, the benefit amounts to ~142 million, and the break-even point occurs after ~23 years.

3.2. Nitrogen Deposition and Critical Load Exceedances

The emissions of NH_3 from mink farms contribute to the total deposition of Nr both directly as NH_3 deposition and indirectly through the transformation of NH_3 to NH_4^+-containing particles. Both NH_3 and particles containing NH_4^+ deposit through dry and wet deposition processes, and the results for both deposition pathways as well as the total deposition calculated with the DEHM are presented for the five administrative regions in Denmark in Table 3.

Table 3. Concentration of NH_3 and dry, wet, and total deposition of Nr modelled including all emission sources (black). Percentage contribution to the concentration and deposition (red) from emissions from mink farming in Denmark. All results are calculated with the DEHM and presented for the five administrative regions of Denmark. All numbers represent mean values for the meteorological years 2017–2019.

Region	NH_3	NH_3 Cont.	Dry Nr	Dry Nr Cont.	Wet Nr	Wet Nr Cont.	Total Nr	Total Nr Cont.
	μgN/m³	%	kgN/ha	%	kgN/ha	%	kgN/ha	%
North Jutland	0.96	6.4	6.95	4.9	5.51	1.8	12.5	3.5
Mid Jutland	1.11	6.1	7.62	4.6	5.50	1.7	13.1	3.4
Southern Denmark	1.33	3.5	8.48	3.0	6.08	0.9	14.6	2.1
Capitol region	0.68	1.8	5.90	0.7	4.71	0.4	10.6	0.6
Zealand	0.95	1.7	6.40	1.1	4.78	0.4	11.2	0.8
Σ DK (land)	1.09	4.4	7.43	3.4	5.50	1.2	12.9	2.5
Σ DK (marine)			2.38	1.3	3.71	0.5	6.09	0.8

The numbers in black in Table 3 present the ambient average NH_3 concentration and the total Nr deposition to all land surfaces in each of the five administrative regions covering Denmark. Additionally included is the ambient average NH_3 concentration for the country as a whole and the sum of the Nr deposition to all Danish land and marine areas. All emission sources, national and international, are included in these concentrations and depositions. The numbers in red in Table 3 show the percentage contribution to the average concentrations, respectively, the sum of depositions, from Danish emissions of NH_3 from mink farming.

In general, the largest ambient average concentrations of NH_3 are observed in the *Mid Jutland* and *Southern Denmark* regions. This can be explained by the higher intensity of agricultural activities in the western/southern part of Denmark and in the northern part of Germany. This distribution is also evident in Figure 4, left, showing the modelled ambient average concentration of NH_3. For the sum of Nr deposition, the highest values are found in *North* and *Mid Jutland* as well as in *Southern Denmark*, and the lowest values are found in *Zealand* and the *Capitol region*. The two latter regions are both located in the eastern part of the country.

Considering the mink farms specifically, the largest farms in 2019 were located in *North Jutland* and *Mid Jutland*. This is also reproduced in the results from the calculations with the DEHM presented in Table 3 in red, where the highest contributions to the concentration of NH_3 from mink farming are seen in these two regions. Dry deposition is the most important pathway for NH_3, and the contribution to dry deposition from mink farming is around 5% for Nr for the *North Jutland* and *Mid Jutland* regions. For Denmark as a whole, emissions of NH_3 from mink farming in 2019 contributed 4.4% to the average NH_3 concentration level and 0.8% to the total deposition of Nr (averaged over three years of meteorological data for the time period 2017–2019).

Figure 6 shows the spatial distribution of the dry, wet, and total delta-depositions of Nr averaged over 2017–2019 across Denmark, calculated with the DEHM. To obtain the dry deposition values in each grid cell, the dry deposition is calculated for each surface type included in the model, and the resulting deposition is then based on the land cover weighted deposition.

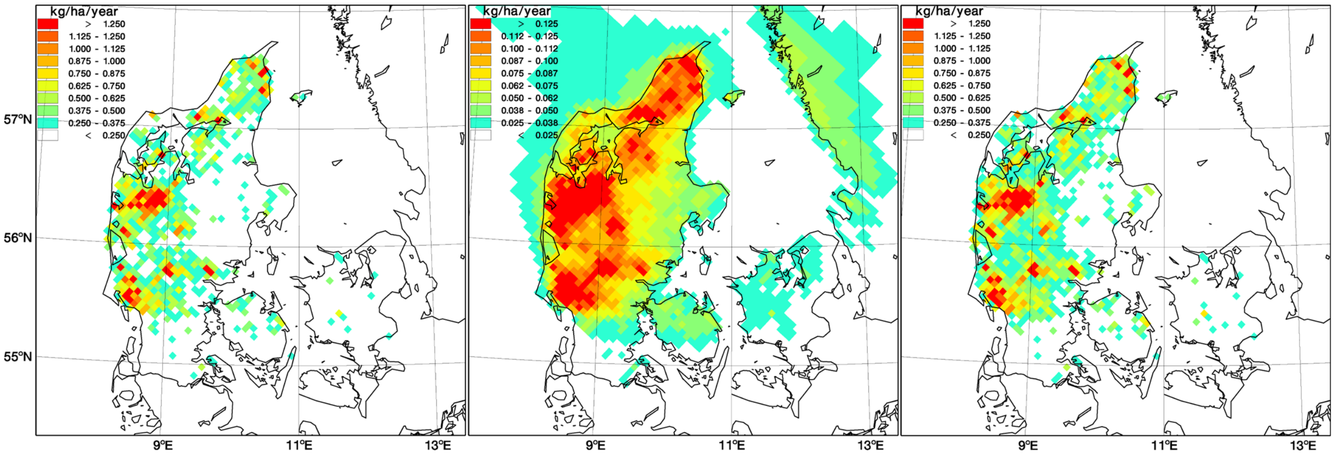

Figure 6. Gridded values of dry (**left**), wet (**centre**), and total (**right**) delta-depositions of Nr in kg/ha/year, calculated with the DEHM on a 5.56 km × 5.56 km spatial resolution based on 2019 emissions and averaged over model runs with meteorological data for the time period 2017–2019.

3.2.1. Local-Scale Deposition of Nr

Using the methodology described earlier, the local-scale calculated NH_3 dry deposition is combined with the gridded dry depositions of the rest of the Nr components and the wet deposition of all Nr components from the DEHM. The resulting detailed map of the total Nr deposition for Denmark for emissions from mink farms is shown in Figure 7. The deposition pattern naturally reflects the distribution of mink farms (compare to Figure 2) The proximity of mink farms to sensitive nature areas is also clearly visible in the zoom over Northeast Jutland (sensitive nature areas marked with grey in Figure 7).

3.2.2. Critical Load Exceedances

Many nature areas in Denmark are subject to Nr deposition exceeding the critical load applicable for the area. Based on the results for local-scale deposition from 2019 mink farming emissions, it is possible to calculate the reduction in area with critical load exceedance that will occur when there are no longer emissions from mink farming. Table 4 shows the size of the areas with exceedance of the critical load for the three main categories of sensitive nature for the two scenarios *with* and *without* 2019 point source emissions from mink farming in Denmark.

From Table 4, it can be seen that the complete cessation of point source emissions from Danish mink farming reduces the area of sensitive non-forested nature with critical load exceedances in Denmark by ~4000 ha. The area of NH_3-sensitive forest with critical load exceedance is also reduced by ~10,600 ha. In total, sensitive nature with a Nr deposition above the critical load will be reduced by ~10% in terms of area when there are no emissions of NH_3 from mink farming.

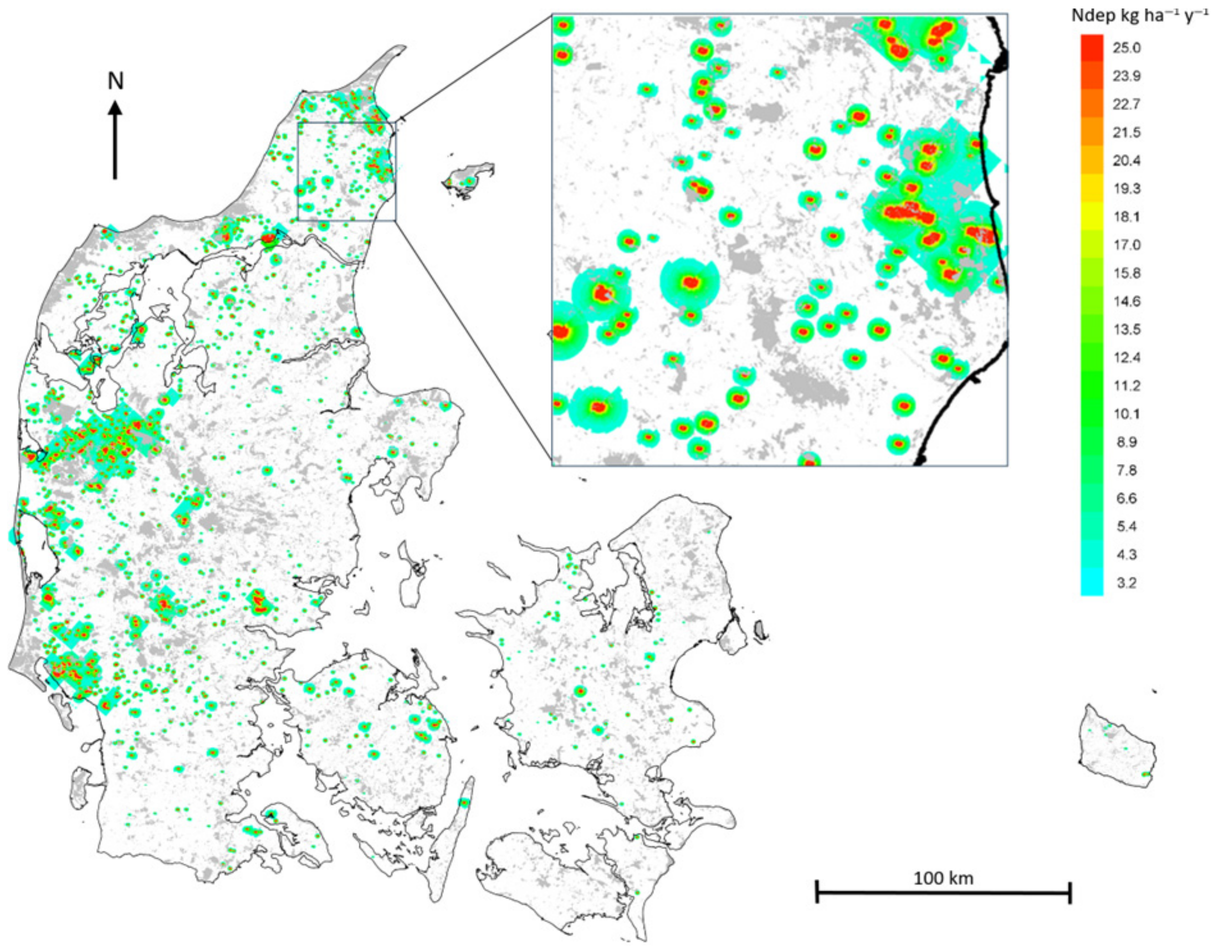

Figure 7. Nr deposition arising from 2019 emissions from mink farming only, calculated as a combination of the local-scale modelled NH_3 dry deposition from dry deposition functions and the DEHM-modelled Nr dry and wet deposition (minus NH_3 dry deposition). The grey marked areas in the plot correspond to sensitive nature areas.

Table 4. Calculated area with critical load exceedances based on the two scenarios with and without the 2019 point source emissions from mink farming in Denmark for the three main categories of sensitive nature including a few sub-categories.

Area with Exceedance of Critical Load (ha)	With Mink	Without Mink	Difference	%
Category 1: NH_3-sensitive light-open nature in Natura 2000	37,353	37,099	254	0.7
- NH_3-sensitive forest in Natura 2000	10,716	10,962	−246	−2.3
- other heathland and dry grassland in Natura 2000	843	754	90	11
Category 2: Larger heathland and grassland areas, Natura 2000	4778	3740	1038	22
- raised bogs, lobelia lakes, outside Natura 2000	367	367	0	0
Category 3: All NH_3-sensitive areas, outside Natura 2000, not included in Categories 1 and 2.	29,484	26,658	2826	9.6
- NH_3-sensitive forest, outside Natura 2000.	61,273	50,626	10,647	17
Total	144,814	130,206	14,609	10

The cost for eutrophication of sensitive nature areas is difficult to calculate and not yet included in the EVA system. An attempt to compare the cost for eutrophication to the estimated socio-economic benefits related to reduced effects on human health from reduced mink farming is to consider the restauration cost for severely eutrofied (non-forested) nature areas. Given an approximate restauration cost of EUR 27,000 pr ha [59], the present case with 4000 ha of sensitive nature affected represents a (one-time) socio-economic benefit of ~EUR 110 million, corresponding to ~77% of the annual benefits estimated for health effects attributed to air pollution.

4. Conclusions/Discussion

Emissions of NH_3 from applied manure from mink are not included in this study due to the lack of data. This will underestimate the contribution from mink to the atmospheric concentration of NH_3 and thereby $PM_{2.5}$, leading to an overall underestimation of the health impacts. It will also underestimate the contribution from mink to the deposition of Nr, calculated with the DEHM and the deposition functions from OML-DEP on the local scale. The area-based emissions from manure application of NH_3 in general constitute about one-third of the total NH_3 emission in Denmark [60]. The share is probably a little smaller for mink, but the application of mink manure takes place relatively closer to nature areas due to the location of the mink farms. With this in mind, the benefits for nature areas and human health from closing the mink farming in Denmark could be up to 50% higher than estimated in this assessment.

NH_3 is also subject to long-range transport, and although emissions of NH_3 from Danish mink farming mainly deposit on Danish land (and water areas) according to the calculations with the DEHM, there can also be a substantial contribution and corresponding effects from the deposition of Nr from Danish mink farming abroad. This impact is also not included in the present assessment.

In conclusion, the socio-economic impact for human health and critical load deposition of closing the mink sector down constitutes an annual benefit. The reduced health impacts correspond to an annual benefit of ~EUR 142 million, and there is also a one-time benefit from reduced eutrophication of ~EUR 110 million. Compared to the compensation cost of ~EUR 3200 million, it is concluded that over a time period of ~22 years, the benefits of closing the mink sector break even with the costs from compensation to mink farmers, assuming that the mink sector activities are closed for good.

In the review performed by Wyer et al. [26], the results showed that emissions from agricultural activities constitute ~90% of the total emissions of NH_3 and contribute to 50% of the ambient $PM_{2.5}$ in Europe. They concluded that one of the most efficient ways to reduce $PM_{2.5}$ is to reduce global NH_3 emissions from agriculture. In 2019, emissions from all Danish agricultural activities constituted ~95% of the national emissions of NH_3 [61], of which ~7% were from mink farming. The emissions of all air pollutants from the Danish agricultural sector were, through reactions with other components in the atmosphere, associated with ~63% of the ambient concentration of $PM_{2.5}$ arising from Danish sources in 2019. Agricultural emissions were also responsible for ~20% of the annual number of premature deaths and ~19% of the total socio-economic costs of air pollution attributable to Danish emission sources in Denmark [62]. Both Wyer et al. [26] and De Vries [6] show that the socio-economic benefits for human health will outweigh the costs of reducing NH_3 emissions, e.g., by introducing better technology for manure handling. In the present assessment, the costs are not from reducing NH_3 emissions but from compensation to former mink farmers, and these costs are higher.

Focusing on the ~10% reduction in nature areas with critical load exceedances from reducing mink farming emissions to zero, it is interesting to compare this number with the ~7% that the mink emissions constitute of the entire Danish NH_3 emissions. The relatively higher contribution of NH_3 emissions from mink farming to the critical load exceedance compared to the emission contribution from mink farming is linked to the fact that the mink farms are located close to the sensitive nature areas. The benefit of reducing this specific emission source is therefore relatively larger than the reduction itself.

Another perspective regarding the benefits for society is that the reduction in national total NH_3 emissions obtained as a result of closing the mink farming sector ensured that Denmark was able to attain the reduction target goal for NH_3 emissions in 2020. This is required by the UNECE Gothenburg protocol on long-range transboundary air pollutants (https://unece.org/environment-policy/air, accessed 20 March 2025) and the EU NEC Directive (2016/2284/EU). With this protocol, Denmark had agreed to reduce national total NH_3 emissions by 24% from 2010 to 2020. As of 2021, it had only been possible to reduce the national total emission by ~17–18%, thus making it difficult to reach the reduction target. However, by introducing the ban on mink production and thereby reducing the national NH_3 emissions, Denmark was able to reach its commitment with respective to the directive. With the closing of the mink sector, the projections for 2030 also show compliance with the NEC 2030 targets.

As of 2023, the ban on mink farming has been lifted. Due to the complete eradication of the mink farming sector, leading also to the collapse of supply chains, the sector has only slowly started returning to Danish agriculture.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos16080966/s1, Table S1: Health effects (cases) and socio-economic costs (1000 €) in Europe (EU) and Denmark (DK) attributed to the air pollution arising directly from emissions of NH_3 from mink farming in Denmark in 2019. All numbers represent meteorological data for the year 2017; Table S2: Health effects (cases) and socio-economic costs (1000 €) in Europe (EU) and Denmark (DK) attributed to the air pollution arising directly from emissions of NH_3 from mink farming in Denmark in 2019. All numbers represent meteorological data for the year 2018; Table S3: Health effects (cases) and socio-economic costs (1000 €) in Europe (EU) and Denmark (DK) attributed to the air pollution arising directly from emissions of NH_3 from mink farming in Denmark in 2019. All numbers represent meteorological data for the year 2019; Figure S1: Comparison of measured (y-axis) and modelled (x-axis) annual mean atmospheric concentrations of NH_3; Figure S2: Comparison of measured (y-axis) and modelled (x-axis) annual mean atmospheric concentrations of NH_4^+; Figure S3: Comparison of measured (y-axis) and modelled (x-axis) annual mean atmospheric concentrations of the sum of NH_3 and NH_4^+ (denoted SNH_4); Figure S4: Comparison of measured (y-axis) and modelled (x-axis) annual mean atmospheric concentrations of $PM_{2.5}$.

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