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Costs and benefits of agricultural ammonia emission abatement options for compliance with European air quality regulations

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Abstract

Background: In Europe, ammonia (NH_3) emissions strongly contribute to fine particulate matter (PM2.5) pollution and associated premature human mortality. The National Emission Ceilings Directive 2016/2284/EU has set an obligation for all European Union countries to reduce the NH_3 emissions by 6%, relative to 2005, by 2020. This study aims to assess the costs and benefits of four NH_3 emission abatement options for the compliance of the agricultural sector with the commitments of the European air quality regulatory framework. A regional atmospheric model (WRF/Chem) was used to assess the effects of regulating NH_3 emissions reductions on PM2.5 concentrations over Europe. Non-market valuation techniques (value of statistical life) were used to monetize the associated health outcomes.

Results: We calculated that 16 out of the 28 EU member states exceeded their 2020 NH_3 emission ceilings in 2016. The highest exceedances from the 2020 emission commitment level occurred in Latvia (15%), Germany (12%) and the UK (12%). Simulation of the required NH_3 emission reduction by WRF/Chem showed that relatively large reductions in PM2.5 concentrations occur over central-western Europe and the UK. The largest health benefits (> 5% reduction in premature mortality) were found for Scandinavia. The economic benefit from avoided premature deaths over Europe amounts to 14,837 M€/year. The costs of four NH_3 emission abatement options, where each would fully achieve the required emission reduction, range from 80 M€/year for low nitrogen feed to 3738 M€/year for low-emission animal housing, with covered manure storage (236 M€/year) and urea fertilizer application (253 M€/year), in between.

Conclusion: Our analysis indicates that the costs of compliance by the agricultural sector with the commitments of the European air quality regulations are much lower than the economic benefit. Thus, much more ambitious reduction commitments for NH_3 emissions could be applied by the EU-28. The monetization of the health benefits of NH_3 emission abatement policies and the assessment of the implementation costs can help policy-makers devise effective air pollution control programmes.

Keywords: Ammonia emissions, WRF/Chem, Value of statistical life, PM2.5 in Europe, Premature mortality, CAP

Background

Air pollution, especially fine particulate matter with a diameter smaller than 2.5 µm (PM2.5), has been associated with many adverse health impacts. Exposure to PM2.5 and ozone is considered responsible about for 4.55 million premature deaths annually worldwide, of which 274,000 per year (i.e., 6%) are reported for European Union (EU) [46]. Recent studies have revealed a large (40% or higher) contribution of agricultural emissions to PM2.5 pollution in many European countries [6, 45]. For example, in Germany the contribution by agriculture to PM2.5 and associated premature mortality is about 45% [45].

Ammonia (NH_3) emissions, which originate for 96% from agricultural activities, significantly contribute to the formation of secondary particulate matter and in particular to the formation of PM2.5 [7]. Giannakis et al. [31] modelled the effect of a 20% increase in the output of

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the EU-28 agricultural sector on air pollution in Europe. Their findings indicate a large increase of PM2.5 concentrations, the highest of which would occur over the northern Balkan countries (Bulgaria and Romania) and northern Italy. The regulation of agricultural NH_3 emissions has been considered the most effective control strategy for reducing PM2.5 in Europe [28, 34, 49]. Pozzer et al. [56] found that a 50% decrease of NH_3 emissions could reduce the annual, geographical average near-surface PM2.5 concentrations by about 11% across Europe, while with maximum emission controls up to 35% reduction would be possible.

Significant progress towards the reduction of anthropogenic air pollution emissions has been achieved over the past 20 years in Europe, mainly driven by policy regulations such as the first national emission ceilings (NEC) directive (2001/81/EC). Most significantly, from 2005 to 2016 sulphur dioxide (SO_2), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOC) and PM2.5 emissions fell by 70%, 37%, 28% and 21%, respectively [23]. However, agriculture is the sector in which air pollutant emissions has decreased least. Within the EU-28, emissions of NH_3 from agriculture have decreased by a mere 5% from 2005 to 2013 [21]. On the contrary, from 2013 onwards, NH_3 emissions have slightly increased again (+3% from 2013 to 2016) [21].

The main legislative instrument to achieve the 2030 objectives of the Clean Air Programme is the National Emission Ceilings Directive 2016/2284/EU, which sets national reduction commitments for EU-28 countries for five important atmospheric pollutants, namely, sulphur dioxide (SO_2), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOC), ammonia (NH_3) and PM2.5. Each EU-country is required to formulate and implement a national air pollution control programme by 2019, and every 4 years thereafter set out the measures to comply with the 2020 and 2030 reduction commitments (Directive 2016/2284/EU). For agriculture, each EU-country is required to establish a national advisory code of good agricultural practice to control NH_3 emissions.

Contrary to most production sectors, there is no extensive body of EU legislation focused on reducing air pollution from agriculture. Little support for NH_3 reduction has been provided by the Common Agricultural Policy (CAP) [17], although within the second pillar of the CAP, i.e., rural development policy, a number of emission-reducing support measures exists such as the measure 'investments in physical assets' (e.g., investments in low-emission manure storage and spreading facilities), as well as the 'agri–environment–climate' measures. However, the current reform of the legislative framework of the CAP for the period 2021–2027 identifies the improvement of air quality as a priority [19]. Moreover, agriculture was a focus topic of the First Clean Air Forum organized by the European Commission in Paris (November 2017), where over 300 participants from government, industry and non-governmental organizations shared their views and perspectives for reducing NH_3 emissions from agricultural activities [18]. Agriculture is also one of the three thematic topics of the Second Clean Air Forum (2019) of the European Commission in Slovakia in November 2019.

According to the theoretical framework of Houlton et al. [39], the first target for solving the global nitrogen balance is the improvement of nitrogen-use efficiency for food production. However, a quantitative analysis of the costs and benefits of technologies improving nitrogen-use efficiency is currently missing [39]. We aim to fill this gap and empirically investigate the costs and benefits of regulating NH_3 emissions for the compliance of the agricultural sector of EU countries with the commitments of the National Emission Ceilings Directive 2016/2284/EU. The specific objectives of the study are: (i) to estimate the required national NH_3 emission reductions across the EU-28; (ii) to model the effects of these reductions on PM2.5 concentrations over Europe; (iii) to estimate and monetize the resulting reduced premature mortality; (iv) to assess the costs of the required NH_3 emission abatement options.

Methods

National ammonia emission reduction commitments by 2020

The National Emission Ceilings Directive 2016/2284/EU has set an obligation for all EU countries to reduce the NH_3 emissions by 6%, relative to 2005, by 2020. By 2030 a more ambitious reduction commitment is set at 19%. Here, we identify which countries have exceeded their 2020 NH_3 emission ceilings in 2016 and estimate the required reduction of NH_3 emissions to comply with the 2020 commitments.

Atmospheric chemistry model

The Weather Research and Forecast model coupled with the chemistry module (WRF/Chem) [24] was used in this study to assess the effects of reduction in NH_3 emissions on PM2.5 concentrations over Europe. WRF/Chem is a fully coupled regional atmospheric transport and chemistry model based on the meteorological core of the WRF model [33], which includes various options of gas-phase chemistry and aerosol microphysics mechanisms. The model uses a terrain-following hydrostatic-pressure vertical coordinate system. In this study 27 layers are used, from the surface up to 50 hPa, with an average height of 70 m for the model layer closest to the surface. Table 4 summarizes the configuration of the model used in this study.

WRF/Chem has been widely used in atmospheric studies across Europe and evaluation under various conditions has shown that the WRF/Chem performance over Europe qualifies as state-of-the-art modelling system [8, 60]. Kushta et al. [44] compared WRF/Chem simulated mean annual PM2.5 concentrations, using a similar configuration as the current study, against observed PM2.5 concentrations from the AIRBASE monitoring network over Europe, and concluded that more than 95% of the simulated data fell within a factor two of the observations. For health assessment studies Kushta et al. [44] showed that the uncertainties derived from the model performance are minor compared to the uncertainties introduced by the assumptions related to exposure risk factors. In that study, the authors also found that there was only 10% difference between the mortality rates over the EU-28 from satellite-derived PM2.5 mean annual concentrations and those derived from the WRF/Chem simulations.

We conducted year-long simulations with meteorological forcing from the National Center for Environmental Prediction (NCEP) global forecast system (GFS) and chemical boundary conditions from global simulations with MOZART-4 (Model for Ozone and Related chemical Tracers version 4; [16] for the year 2015. Emission estimates were taken from the global emission dataset EDGAR-HTAP v2 at a resolution of 0.1° × 0.1° for nitrogen and sulphur oxides (NOx and SOx), non-methane volatile organic compounds (NMVOC), carbon monoxide (CO), ammonia (NH_3) and fine and coarse particulate matter (PM2.5 and PM10) [41]. Simulations were performed at a horizontal grid spacing of 50 km covering the wider European region shown in Fig. 1. Two annual simulations were performed: (i) simulation 1 with the standard emission inventory available in WRF/Chem (WCcntr) and (ii) simulation 2 with the country-based NH_3 emission reductions according to the national emission reduction commitments from 2020 (WC_{NH3}).

Health impacts

The annual mean PM2.5 concentrations derived from the two simulations of WRF/Chem were used to estimate reduced premature mortality rates for a range of related diseases and age groups, based on integrated exposure–response (IER) functions [10]. For the calculation of the relative risk (RR) factors we used the updated parameters used for the global burden of disease study (GBD) for 2015 [13]. Recently, new IER functions have become available, indicating much higher premature mortality rates [11], but here we apply the estimates that are consistent with the GBD [13]. The IER functions were applied to account for health effects of PM2.5 related to ischaemic heart disease, cerebrovascular disease, lower respiratory tract infections, chronic obstructive pulmonary

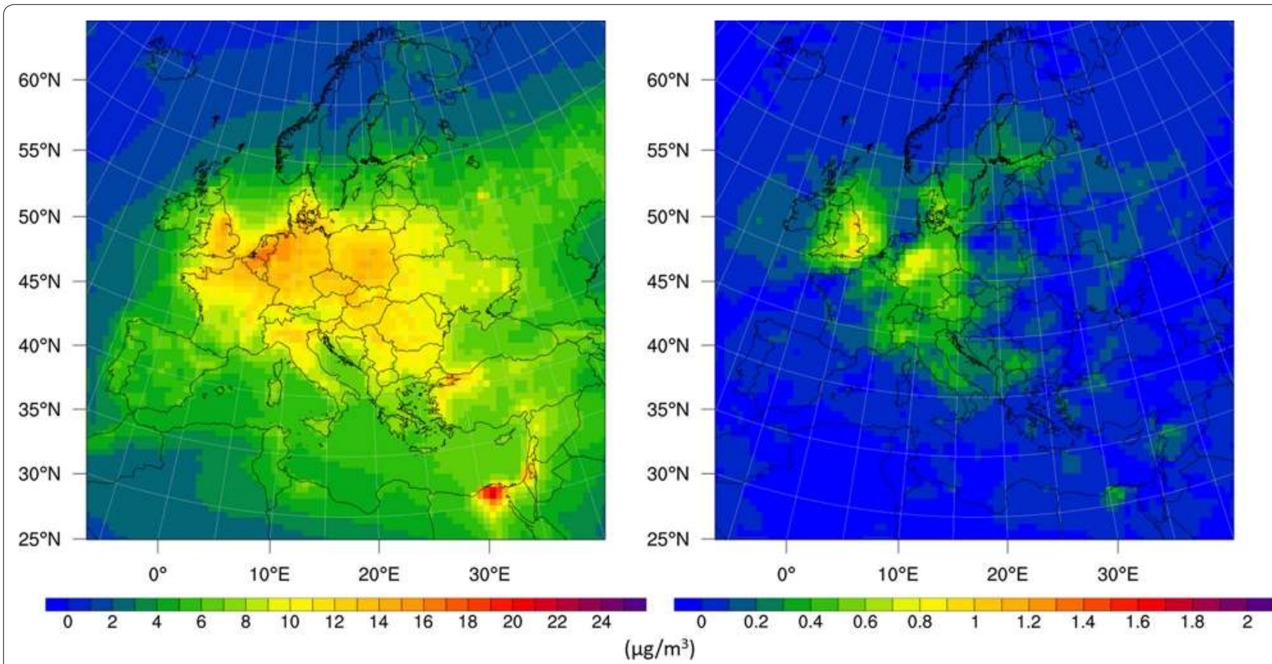

Fig. 1 Mean annual PM2.5 surface concentrations (μg/m^3) from the control (WCcntr) simulation (left) and difference in PM2.5 concentrations (μg/m^3) between the WCcntr and the NH_3 emission reduction (WC_{NH3}) simulation (right)

disease and lung cancer. Note that the new IER functions of Burnett et al. [11] include additional non-communicable diseases, not yet accounted for by the GBD [13]. Hence our results should be regarded as conservative health impact estimates. The respective burden of disease was analysed for the following age groups: below 5 years, 5–14, 15–29, 30–49, 50–69, and 70 and older. Country-level baseline mortality rates for each of the diseases representative of the year 2015 and the population data for the countries included in our domain were taken from the WHO Global Health Observatory (http://www.who.int/gho/database/en/). We estimate a 95% confidence interval with the use of the IER functions, as described in Cohen et al. [13] and in GBD [26], for the uncertainty estimates of the economic value of the reduction in NH_3 emissions (see "Economic valuation of mortality").

Economic valuation of mortality

The monetary valuation of the risk of premature death relies on non-market valuation methods. The value of statistical life (VSL) is the most widely used metric to monetize premature mortality risks associated to air pollution [28, 51] and was applied in this study to calculate the benefits of policies reducing NH_3 emissions from agriculture. The VSL is the marginal rate of substitution between wealth and mortality risk, and is defined as the rate at which people trade off income for mortality risk reduction [35]:

$$\mathrm{VSL} = \frac{\partial \mathrm{WTP}}{\partial p}, \tag{1}$$

where p is the mortality risk; WTP is the individual's willingness to pay to reduce mortality risk by Δp.

Similar to Ghude et al. [27] and Giannadaki et al. [28], we used the *VSL* base value of 3 million USD (in 2005-USD) derived by the OECD [51] meta-analysis study to estimate the VSL for the individual countries (EU and non-EU; see Table 5), adjusting for differences in income and economic growth as suggested in OECD [51, 52]. The equation is given as:

$$\mathrm{VSL}_{i,2016} = \mathrm{VSL}_{\mathrm{OECD},2005} \times \left(\frac{Y_{i,2005}}{Y_{\mathrm{OECD},2005}}\right)^{\beta} \times \left(1 + \%\Delta P_{i,2005-2016} + \%\Delta G_{i,2005-2016}\right)^{\beta}, \tag{2}$$

where $\mathrm{VSL}_{i,2016}$ is the adjusted *VSL* for country i in 2016; $\mathrm{VSL}_{\mathrm{OECD},2005}$ is the *VSL* base value for OECD countries in 2005; $Y_{i,2005}$ is the GDP per capita in country i in 2005 in PPP (purchasing power parity); $Y_{\mathrm{OECD},2005}$ is the average GDP per capita in OECD countries in 2005 in PPP; β is the income elasticity of VSL and equals to 0.8 as recommended by OECD [51, 52]; $\%\Delta P_{i,2005-2016}$ and $\%\Delta G_{i,2005-2016}$ are price inflation/deflation and GDP per capita increase/decrease in country i between 2005 and 2016, respectively. We use the expected VSL range of 1.5–4.5 million USD [51] for the uncertainty estimates of our analysis, as explained below.

The annual economic value of reduction in NH_3 emissions (*EV*) was calculated by multiplying the number of premature deaths expected to be prevented in a given year in country i (L_i) with the respective VSL_i as follows:

$$\mathrm{EV} = (L_i) \times (\mathrm{VSL}_i). \tag{3}$$

We use the fractional uncertainties of L_i and VSL_i to estimate the uncertainty range of the economic value of reduction in NH_3 emissions (EV) as follows [25]:

$$\delta \mathrm{EV} = \sqrt{\left(\frac{\delta L}{L}\right)^2 + \left(\frac{\delta \mathrm{VSL}}{\mathrm{VSL}}\right)^2} \times \mathrm{EV}, \tag{4}$$

where δL is the absolute value of the upper or lower bound minus the mean of L and similarly for δVSL.

Costs of ammonia emission abatement options

A set of measures for reducing NH_3 emissions from agriculture is included in Directive 2016/2284/EU, such as livestock feeding strategies, low-emission manure storage systems, low-emission animal housing systems, techniques for limiting NH_3 emissions from the use of mineral fertilizers. The efficiency of these measures has been investigated for the EU by Klimont and Winiwarter [42] and Oenema et al. [53]. Oenema et al. [53] used the Greenhouse gas-Air pollution INteractions and Synergies (GAINS) model, developed by the International Institute of Applied Systems Analysis (IIASA), to estimate the cost of NH_3 emission abatement options in € per kg nitrogen (kg N) removed per year.

Here, we selected four NH_3 emission abatement options, three for the livestock sector: (i) low nitrogen feed; (ii) manure storage capacity; (iii) low-emission animal housing; and one for the crop sector: (iv) techniques to improve or substitute urea fertilizer application. These four measures form the basic instruments for establishing the national advisory code of agricultural practice to control NH_3 emissions according to the UNECE Framework Code for Good Agricultural Practice for Reducing Ammonia Emissions of 2014 (Directive 2016/2284/EU). We computed the total annual costs for 2016, for each measure, based on Oenema et al. [53], for the countries that exceeded their national NH_3 emission ceilings (see "Exceedance of 2020 national ammonia emission reduction commitments"). The computed costs cover the total cost of achieving a country's required emission reduction, while in reality a country could select to apply a combination of these four measures. For the uncertainty range of the costs of the emission control measures we use the 25th and 75th percentile values specified by Oenema et al. [53].

Results and discussion

Exceedance of 2020 national ammonia emission reduction commitments

We calculated that 16 out of the 28 EU member states exceeded their 2020 NH_3 emission ceilings in 2016. The reduced NH_3 emissions (tonnes) required to meet air quality targets for the 16 countries are presented in Table 1. The highest deviations from the 2020 emission commitment level (> 10% above the maximum 2020–2029 emissions) occurred in Latvia (15%), Germany, Estonia and the UK (12%), Sweden (11%) and Finland (10%) (Table 1).

Air quality impact

The mean annual modelled PM2.5 surface concentrations over Europe and the reduction in PM2.5 burden due to the reduction of NH_3 emissions are shown in Fig. 1. The difference in PM2.5 concentrations (μg/m^3) is expressed as $WC_{cntr} - WC_{NH3}$, where WC_{cntr} and WC_{NH3} represent the mean annual surface concentrations of PM2.5 from the control simulation (cntr) and from the NH_3 emission reduction simulation (NH_3). The PM2.5 concentrations and the impact of reducing NH_3 emissions were assessed for each of the 16 selected EU countries, for the EU-28 and for a number of neighbouring countries (see Table 5).

Near-surface modelled PM2.5 concentrations exhibit a peak over Central Europe and Poland and Benelux countries with mean annual concentrations reaching 16–18 μg/m^3, which is below the current EU limit of 25 μg/m^3, but well in excess of the guideline of 10 μg/m^3 of the World Health Organization (WHO). Other regions with pronounced PM2.5 levels include the northern part of Italy with local sources such as transport and diffuse regional sources such as industrial fossil fuel and biomass burning [55] and major megacities in the Southeastern Europe such as Istanbul, Greater Cairo area and along the coast of Israel where major coal power plants are located [3].

The distribution of the differences in near-ground concentrations from the application of the NH_3 emission abatement measures shows a PM2.5 maximum over central-western Europe, collocated to a large extent with the required NH_3 emission reductions to meet the 2020 commitments of the National Emission Ceilings Directive 2016/2284/EU, especially over Germany and UK (see Table 1). Very small differences occur over Eastern Europe with concentrations affected by less than 0.3 μg m^{-3}. Bessagnet et al. [9] quantified the impact of additional reductions of NH_3 emissions beyond the Gothenburg Protocol requirements on PM2.5 concentrations in the EU-27 and demonstrated that the most

Table 1 Reported NH_3 emissions for 2005 and 2016, NH_3 emissions reduction to meet 2020 emission commitment level, for the 16 EU countries that exceeded this level in 2016

Countries	Reported NH_3 emissions in 2005 (tonnes/year)	NH_3 emissions reduction to meet 2020 commitments (%, relative to 2005)	Reported NH_3 emissions in 2016 (tonnes/year)	NH_3 emissions reduction to meet 2020 commitments (%, relative to 2016)	NH_3 emissions reduction to meet 2020 commitments in 2016 (tonnes)
Bulgaria	42,915	3	42,282	2	654
Denmark	83,121	24	70,769	11	7597
Germany	580,691	5	629,236	12	77,580
Estonia	9373	1	10,563	12	1284
Ireland	110,574	1	115,528	5	6060
Spain	445,102	3	448,825	4	17,076
France	585,320	4	591,415	5	29,508
Latvia	11,906	1	13,947	15	2160
Luxembourg	5689	1	6189	9	557
Hungary	80,226	10	78,417	8	6214
Austria	60,024	1	63,791	7	4367
Portugal	47,810	7	45,716	3	1253
Slovakia	33,591	15	28,960	1	408
Finland	31,677	20	28,132	10	2790
Sweden	48,986	15	46,747	11	5109
United Kingdom	241,296	8	253,045	12	31,053
EU-16	2418,301	6	2,473,562	8	193,668

important reductions took place in the main NH_3 source areas (e.g., over the south of England, north of France, Germany, Czech Republic and Poland), i.e., the agriculturally intensive regions; they found that the efficiency of reductions in NH_3 emissions was highest for relatively large reduction rates. Similarly, Backes et al. [4] analysed the source distribution patterns in Europe using the emission model SMOKE, and demonstrated that the largest NH_3 emissions occur in hotspots where the livestock density is high, for example in intensively housed animal production systems in the Po-valley, Denmark, Brittany, Belgium and the Netherlands.

Ammonia emissions contribute to the formation of the main two inorganic aerosol components over Europe, ammonium nitrate (NH_4NO_3) and ammonium sulfate ($(NH_4)_2SO_4$), with the first being most abundant near source regions and the second further downwind due to the slower formation rate and its pronounced stability [31]. Ammonium nitrate results from the reaction between ammonia and nitric acid, a process that competes with the slower-rate neutralization of sulfuric acid in the atmosphere that leads to the formation of the more thermodynamically stable ammonium sulfate aerosols. Park et al. [54] showed that during transport away from the NOx and NH_3 source areas, and especially at relatively high temperatures, e.g., during summer, NH_4NO_3 can rapidly volatilize, in contrast to $(NH_4)_2SO_4$. Thus, NH_4NO_3 is mostly present near source areas and contributes to PM2.5 over emission source regions. This process explains that the reduction imposed in this sensitivity test does not strongly affect aerosol concentrations remote from the emission sources, with larger differences collocated with main emitting countries (and the ones with the larger reduction in NH_3 primary emissions).

It is anticipated that NH_3 control effectiveness could be influenced by simultaneous changes in other pollutants such as SO_2 and NOx [5]. These changes can either come about as a result of interactions between industrial sectors as described in Giannakis et al. [31] and/or derive from additional measures aimed at the most strongly SOx and NOx emitting sectors such as traffic, energy production and consumption and several manufacturing industries.

Ammonia emission control measures may lead to improved air quality and reduced premature mortality, however, they could affect the intensity and spatial distribution of acid rain impacts on ecosystems. Recently, Liu et al. [48] showed that while ammonia emission abatement measures could prove a strategic option to mitigate haze pollution, it could also worsen the acid rain intensity and spatial distribution in China, possibly partly offsetting the benefit from better air quality and less nitrogen deposition. They concluded that there are, however, region-specific patterns in this complex mechanism. For example, in many soils nitrifying bacteria transform ammonium into nitrate, which enhances acidification. Thus, there is a need for region-specific strategies for multipollutant controls that will benefit both human and ecosystem health. The present study presents an assessment of the benefit that would derive from agricultural NH_3 emission abatement options, rather than considering scenarios in which other sectors/pollutants are being considered as well.

Health assessment

Next, we quantified the potential health benefits over the domain resulting from the reduction of NH_3 emissions (WC_{NH3}). The most positively affected countries, compared to the control run (> 5% reduction in premature mortality), in terms of relative change, are located in Scandinavia, i.e., the reduction in premature mortality was 13% in Finland, that is, 80 less premature deaths per year (95% confidence interval (CI95): 39–110), 9% in Sweden (162, CI95: 87–192) and 9% in Norway (32, CI95: 15–42) as summarized in Table 2. In terms of absolute values of excess deaths that could be avoided with the compliance of agriculture to the commitments of the National Emission Ceilings Directive 2016/2284/EU, Germany is expected to have the largest benefit (930) followed by UK (928) and Italy (448) (Table 6). Here, we have to note that changes in excess mortality do not follow a linear relationship with PM2.5 concentrations. The IER functions tend to "flatten" towards higher PM2.5 concentrations, and air pollution control measures can be particularly effective at relatively low levels [13]. Scandinavian countries have relatively low reference air pollution levels, thus their relative reduction in mortality from PM2.5 is larger than that in more polluted regions. Similar findings were reported by Giannadaki et al. [28] who estimated that large-scale reduction in NH_3 emissions in the EU-28, i.e., by 50%, could reduce associated premature mortality by 18%, resulting in an annual economic benefit of 89 billion USD. They found the largest reductions in premature mortality in Estonia (70%), Finland (58%), Norway (56%) and Sweden (45%).

As mentioned above, the mortality burden estimates in Europe could be higher using the most recent epidemiological models [11, 47, 62, 64], suggesting that improving air quality and applying associated policy measures could potentially lead to greater health benefits than previously thought. In these recent studies, more accurate hazard ratio functions that associate PM2.5 concentrations with the health response have been produced, using new data from additional and geographically extended epidemiological studies, including studies of long-term air pollution exposure that cover the very low and very

Table 2 Reduction in premature mortality resulting from the reduction of ammonia emissions over Europe in 2016

Countries with > 5% reduction in premature mortality	Countries with 2–5% reduction in premature mortality	Countries with 1–2% reduction in premature mortality	Countries with < 1% reduction in premature mortality
Finland	United Kingdom	Bosnia and Herzegovina	Slovakia
Sweden	Denmark	Northern Macedonia	Spain
Norway	Austria	Slovenia	Hungary
Estonia	Germany	Albania	Poland
Ireland	Italy	France	Bulgaria
	Switzerland	Croatia	Latvia
	Luxembourg	Czech Republic	Romania
	Portugal	Belgium	Jordan
		Montenegro	Ukraine
		Serbia	Georgia
		Netherlands	Turkey
		Cyprus	
		Greece	
		Lebanon	

high ends of the PM2.5 concentration range of mean exposures. Burnett et al. [11] used worldwide mortality data from all non-communicable diseases as well as pneumonia instead of the five major ones (ischaemic heart disease, cerebrovascular disease, lower respiratory tract infections, chronic obstructive pulmonary disease and lung cancer) upon which the IER mortality is based. Based on the new Global Exposure Mortality Model (GEMM) described in Burnett et al. [11], Lelieveld et al. [47] showed that the use of the GEMM for Europe results in more than twice the number of premature deaths per year, mostly due to PM2.5 exposure, compared with the Global Burden of Disease estimate that is based on previous IER functions [10, 13, 26]. Wang et al. [64] showed that in California the GEMM approach resulted in a greater PM2.5-associated mortality burden than the more conventional log-linear function (all-cause mortality derived from Krewski et al. [43] and Hoek et al. [37] and the previous IER functions [10]. The authors argue that the true relationship between mortality and PM2.5 exposure has not yet been established. Despite the fact that the uncertainties and discrepancies among the existing concentration response functions in the literature could pose a limitation to the current study and warrant further research, these limitations will be towards higher mortality estimates and associated benefits rather than lower ones. Our findings indicate that the PM2.5 exposure in Europe can have significant health effects, and changes from agricultural policy measures can lead to substantially reduced excess mortality and financial benefits. Recent new epidemiologic evidence strongly corroborates that these substantial health benefits associated with PM2.5 control could have been underestimated.

Cost–benefit assessment of ammonia emission abatement options

The estimated costs of NH_3 emission abatement options over Europe are shown in Table 3. The estimated annual costs for 2016 of NH_3 emission control measures to achieve the emission reduction commitments amount from 80 M€ (uncertainty range (*r*): 70–89 M€) (low nitrogen feed) to 3738 M€ (*r*: 3357–4118 M€) (low-emission animal housing), which correspond to 46 €/year per farm with livestock for low nitrogen feed option and 2176 €/year per farm with livestock for low-emission animal housing option in the 16 EU countries. The highest cost per livestock holding is expected in Germany for both measures, that is, 173 €/year/holding (low nitrogen feed) and 8107 €/year/holding (low-emission animal housing). These cost estimates (80 M€ and 3738 M€) represent around 0.1% and 6.3%, respectively, of the total 2014–2020 European Agricultural Fund for Rural Development (EAFRD) funding of the 16 studied EU countries [20]. Similarly, the estimated annual cost for the covered manure storage option is 236 M€ (corresponding to 137 €/year/farm with livestock), and for improving the application of urea fertilizer option it is 253 M€ (corresponding to 161 €/year/crop farm) in the 16 EU countries.

The annual economic benefit from the avoided premature deaths due to the regulation of NH_3 emissions in the 16 EU countries is 10,370 M€ (*r*: 4843–15,706 M€), which translates into 31€/year per EU-16 citizen (*r*: 15–47 €/

Table 3 Costs of four ammonia emission abatement options, computed based on Oenema et al. [53]—each option would fully achieve the 2020 national emission reduction commitments, in 2016—and benefits of meeting these commitments, derived from WRF/Chem model simulations, integrated exposure–response (IER) functions and value of statistical life (VSL) metric

	Cost of low nitrogen feed (M€)	Cost of covered manure storage (M€)	Cost of improving or substituting urea fertilizer application (M€)	Cost of low-emission animal housing (M€)	Economic benefit of reducing NH_3 emissions (M€)
Austria	1.80 (1.58–2.01)	5.32 (3.34–7.30)	5.70 (5.29–6.11)	84.29 (75.71–92.86)	319.09 (153.96–482.30)
Bulgaria	0.27 (0.24–0.30)	0.80 (0.50–1.09)	0.85 (0.79–0.92)	12.63 (11.35–13.92)	101.19 (49.06–152.72)
Denmark	3.13 (2.75–3.50)	9.26 (5.82–12.70)	9.92 (9.20–10.64)	146.62 (131.70–161.54)	212.31 (101.47–321.09)
Estonia	0.53 (0.47–0.59)	1.56 (0.98–2.15)	1.68 (1.55–1.80)	24.78 (22.25–27.30)	97.63 (47.49–147.79)
Finland	1.15 (1.01–1.29)	3.40 (2.14–4.66)	3.64 (3.38–3.91)	53.85 (48.37–59.33)	295.22 (83.47–478.66)
France	12.15 (10.69–13.61)	35.96 (22.60–49.33)	38.52 (35.72–41.31)	569.48 (511.53–627.44)	848.78 (409.80–1282.79)
Germany	31.94 (28.11–35.78)	94.56 (59.42–129.69)	101.26 (93.92–108.61)	1497.24 (1344.86–1649.62)	3652.42 (1773.67–5514.07)
Hungary	2.56 (2.25–2.87)	7.57 (4.76–10.39)	8.11 (7.52–8.70)	119.92 (107.71–132.12)	164.99 (80.59–249.19)
Ireland	2.50 (2.20–2.79)	7.39 (4.64–10.13)	7.91 (7.34–8.48)	116.95 (105.05–128.85)	173.50 (81.76–261.08)
Latvia	0.89 (0.78–1.00)	2.63 (1.65–3.61)	2.82 (2.61–3.02)	41.69 (37.45–45.93)	26.04 (13.00–39.08)
Luxembourg	0.23 (0.20–0.26)	0.68 (0.43–0.93)	0.73 (0.67–0.78)	10.75 (9.65–11.84)	25.19 (9.28–38.04)
Portugal	0.52 (0.45–0.58)	1.53 (0.96–2.09)	1.64 (1.52–1.75)	24.18 (21.72–26.64)	113.80 (46.21–172.04)
Slovakia	0.17 (0.15–0.19)	0.50 (0.31–0.68)	0.53 (0.49–0.57)	7.87 (7.07–8.67)	92.42 (45.28–139.42)
Spain	7.03 (6.19–7.88)	20.81 (13.08–28.55)	22.29 (20.67–23.91)	329.56 (296.02–363.10)	182.47 (88.59–274.13)
Sweden	2.10 (1.85–2.36)	6.23 (3.91–8.54)	6.67 (6.18–7.15)	98.60 (88.56–108.63)	648.43 (206.38–994.32)
United Kingdom	12.79 (11.25–14.32)	37.85 (23.78–51.91)	40.53 (37.59–43.47)	599.30 (538.31–660.29)	3416.25 (1652.69–5159.09)
EU-16	79.75 (70.18–89.32)	236.05 (148.33–323.77)	252.79 (234.45–271.14)	3737.69 (3357.30–4118.08)	10,369.74 (4842.69–15,705.82)
EU-28	79.75 (70.18–89.32)	236.05 (148.33–323.77)	252.79 (234.45–271.14)	3737.69 (3357.30–4118.08)	13,488.21 (6357.81–20,414.03)
EU-28 and neighbouring non-EU countries	79.75 (70.18–89.32)	236.05 (148.33–323.77)	252.79 (234.45–271.14)	3737.69 (3357.30–4118.08)	14,837.48 (6976.17–22,465.43)

Numbers in parentheses represent uncertainty ranges as described in "Methods"

citizen). The associated annual economic benefit in the 28 EU countries is 13,488 M€ (corresponding to 26 €/year per EU-28 citizen) and over the wider European domain it is 14,837 M€. The largest economic benefits are found for Germany (3652 M€) and the UK (3416 M€), i.e., the countries with the largest deviation in meeting the national emission reduction commitments.

Our estimates indicate that the regulation of NH_3 emissions generates large health and economic benefits for the EU countries implementing the measures but also for the wider region. The relatively low level of emission reduction commitment for NH_3 for EU-28, i.e., 6%, can be achieved by the implementation of a relatively low-cost measure such as low nitrogen feed. The economic benefits from avoided premature deaths over Europe are orders of magnitude greater than the expenditure of implementing the low nitrogen feed abatement option. However, even for the least cost-effective measure (low-emission animal housing) the economic benefits are still fourfold of the costs. The benefit-to-cost ratios of the four NH_3 abatement options range from 186 (*r*: 99–252) for low nitrogen feed to 4 (*r*: 2–5) for low-emission animal housing in Europe, with covered manure storage (63; *r*: 47–69) and urea fertilizer application (59; *r*: 30–83), in between. We have to note that these estimates are conservative because reduced morbidity has not been included, and we used IER functions that should be regarded as providing lower limit results for premature mortality. However, we also need to stress here that a small fraction of society, that is, 1.72 million holders of farms with livestock (for the three NH_3 emission abatement options for the livestock sector) and 1.57 million holders of crop farms (for the NH_3 emission abatement option for the crop sector) in 16 EU countries [22] may have to bear the costs of measures to abate NH_3 emissions, while 510.2 million EU-28 citizens would benefit from the improvement of air quality. The loss of competitiveness of European farmers relative to those in non-EU countries with less stringent environmental policies, and the improvement of public health and economic benefits for the whole society indicate the need of redistributing such costs, for example through financial support of the implementation of NH_3 abatement measures.

Wagner et al. [63] assessed the costs and benefits of manure storage cover and application techniques in Lower Saxony, Germany, and reported similar results as our findings. They found that the implementation of concrete storage covers and slurry injection could reduce NH_3 emissions by 25% amounting to net benefits of 505 M€ and a benefit-to-cost ratio of 4.2. Similarly, Van Grinsven et al. [61] estimated that the social cost of the impacts of agricultural NH_3 emissions in the EU-27 in 2008 was between 10 and 120 billion € per year of which 5–65 billion € were associated with air pollution effects on human health. They concluded that low-cost NH_3 emission abatement measures (e.g., improved *N* use efficiency) could lead to large reduction of air pollution with robust welfare increase. Hill et al. [36] showed that reduced air quality resulting from maize production is associated with 4300 premature deaths annually in the United States, with estimated damages in monetary terms of 39 billion USD. Ammonia emission reductions in maize production can be achieved by interventions such as change in fertilizer type and application method, improvement of nitrogen-use efficiency and switching to crops requiring less fertilizer.

Conclusions

By combining a regional integrated atmospheric model with non-market valuation techniques, we estimated the costs and the benefits of regulating NH_3 emissions from agriculture over Europe. Our analysis indicates that meeting the requirements of national emission reduction commitments applicable from 2020 to 2029 set out in the Directive 2016/2284/EU can generate large health and economic benefits not only for the EU countries implementing the measures, but also for the wider region. Our findings highlight that much more ambitious reduction commitments for NH_3 emissions could be applied by EU-28 countries with relatively minimal costs. Recent analyses of premature mortality attributable to PM2.5 indicate that our results represent a lower limit of the health and economic benefits from NH_3 and other air pollution emission reductions.

The exceedance of economic benefits over farmers' abatement costs may indicate the need of transferring back part of the societal benefit of reduced NH_3 emissions to the farmers in the form of investment support for the abatement measures. The CAP through rural development policy measures could strongly contribute to meeting those emission reduction commitments. Domínguez et al. [15] showed that when subsidies are paid for the application of technological emission mitigation options, the share of mitigation achieved via technologies instead of production changes increases considerably, which has a minimal impact on farmers' profitability. Increasing the support for agricultural modernization and strengthening the training of European farmers could further foster the adoption of new technologies, thus improving the environmental and economic performance of European agriculture [29, 30]. The evaluation of agricultural nonpoint pollution control options for China demonstrated that the combination of subsidies to farmers for reducing fertilizer use with education and training on management techniques can be more successful than either policy option by itself [1]. Similarly, increasing awareness of the large contribution of animal husbandry to air pollution and human health may influence the general public to change the composition of their diet towards plant-based foods [58], while raising consumers' willingness to buy more environmentally friendly food can encourage farmers to adopt more sustainable practices [14].

Our monetization of the costs and the benefits of the compliance of agriculture with the current air quality targets provide European and national policy-makers with information for the formulation of (a) the national air pollution control programmes and (b) the national advisory code of good agricultural practices to control NH_3 emissions. Our estimates can also support rural development policy measures under the new CAP post-2020. Our findings highlight the need for a better integration of agricultural and air quality policies that could further lead to reduced air pollution and health impacts in Europe. Future research could analyse the costs and benefits of NH_3 emission abatement measures at a more disaggregated level, i.e., across agricultural systems. This will allow the formulation of specific recommendations for the different agricultural systems in individual European countries.

Abbreviations

CAP: common agricultural policy; CO: carbon monoxide; EU: European Union; GBD: global burden of disease; GDP: gross domestic product; GFS: global forecast system; IER: integrated exposure–response; MOZART-4: Model for Ozone and Related chemical Tracers version 4; NEC: national emission ceilings; NCEP: National Center for Environmental Prediction; NH_3: ammonia; NMVOC: non-methane volatile organic compounds; NOx: nitrogen oxides; PM2.5: particulate matter with a diameter smaller than 2.5 µm; PM10: coarse particles with a diameter smaller than 10 µm; RR: relative risk; PPP: purchasing power parity; SO_2: sulphur dioxide; SOx: sulphur oxides; UK: United Kingdom; USD: United States Dollar; VSL: value of statistical life; WHO: World Health Organization; WRF/Chem: Weather Research and Forecast model coupled with the chemistry module; WTP: willingness to pay.

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Authors' contributions
EG conceptualized the study and conducted the economic analysis. JK conducted the atmospheric modelling analysis. AB and JL provided advice on the methods. All authors contributed to the writing of the paper. All authors read and approved the final manuscript.

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Competing interests
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Appendix

See Tables 4, 5 and 6.

Table 4 Summary of the model configuration processes used in the study

Process	Option	References
Microphysics	Morrison 2-moment scheme	Morrison et al. [50]
Land surface	NOAH land surface model	Chen and Dudhia [12]
Boundary layer	Yonsei University (YSU) planetary boundary layer	Hong et al. [38]
Cumulus	Grell 3D ensemble scheme	Grell and Devenyi [32]
Surface layer	MM5 similarity surface layer scheme	Zhang and Anthes [65]
Radiation	Rapid radiative transfer model (RRTTM)	Iacono et al. [40]
Gas-phase chemistry	Second-generation regional acid deposition model (RADM2)	Stockwell et al. [59]
Aerosols	Modal Aerosol Dynamics Model for Europe (MADE), Secondary Organic Aerosol Model (SORGAM)	Ackermann et al. [2], Schell et al. [57]

Table 5 Values for VSL in 2016 (with the range in parentheses) for the individual countries (EU and non-EU) studied

Countries	VSL (M€)
Luxembourg	7.73 (3.87–11.60)
Norway	5.18 (2.59–7.77)
Ireland	4.95 (2.48–7.43)
Switzerland	4.59 (2.29–6.88)
Austria	4.19 (2.09–6.28)
Denmark	4.10 (2.05–6.15)
Netherlands	4.03 (2.02–6.05)
Sweden	4.00 (2.00–6.00)
Germany	3.93 (1.96–5.89)
Belgium	3.86 (1.93–5.79)
United Kingdom	3.68 (1.84–5.52)
Finland	3.68 (1.84–5.52)
France	3.44 (1.72–5.16)
Italy	3.32 (1.66–4.97)
Spain	3.10 (1.55–4.65)
Estonia	3.03 (1.52–4.55)
Czech Republic	2.96 (1.48–4.44)
Slovenia	2.93 (1.47–4.40)
Cyprus	2.92 (1.46–4.38)
Turkey	2.88 (1.44–4.31)
Portugal	2.76 (1.38–4.14)
Latvia	2.68 (1.34–4.02)
Hungary	2.63 (1.31–3.94)
Slovakia	2.60 (1.30–3.90)
Romania	2.52 (1.26–3.78)
Poland	2.50 (1.25–3.74)
Greece	2.45 (1.22–3.67)
Croatia	2.31 (1.16–3.47)
Bulgaria	2.06 (1.03–3.09)
Serbia	1.92 (0.96–2.87)
Montenegro	1.91 (0.96–2.87)
Ukraine	1.91 (0.95–2.86)
Lebanon	1.66 (0.83–2.48)
North Macedonia	1.58 (0.79–2.38)
Jordan	1.37 (0.68–2.05)
Bosnia and Herzegovina	1.32 (0.66–1.98)
Albania	1.27 (0.64–1.91)
Georgia	1.24 (0.62–1.87)

Table 6 Reduction in premature mortality resulting from the reduction of ammonia emissions over Europe in 2016

Countries	Number of premature deaths
Germany	930.4 (818.0–1022.5)
United Kingdom	928.2 (809.0–1022.2)
Italy	447.6 (391.0–494.8)
France	246.6 (214.0–273.0)
Poland	176.1 (156.0–192.8)
Sweden	162.1 (87.0–192.3)
Montenegro	143.8 (126.0–158.8)
Serbia	143.8 (126.0–158.8)
Ukraine	120.6 (107.0–131.8)
Czechia	90.0 (80.0–98.5)
Finland	80.3 (39.0–109.9)
Austria	76.2 (66.0–84.4)
Belgium	73.2 (66.0–79.5)
Netherlands	70.6 (62.0–77.1)
Hungary	62.8 (56.0–69.2)
Spain	58.9 (66.0–56.0)
Denmark	51.8 (44.0–57.6)
Bulgaria	49.1 (43.0–53.8)
Switzerland	48.7 (42.0–54.1)
Greece	46.5 (42.0–50.9)
Romania	44.8 (39.0–49.3)
Portugal	41.2 (28.0–45.7)
Croatia	36.4 (32.0–39.8)
Slovakia	35.6 (32.0–38.9)
Ireland	35.0 (29.0–37.4)
Estonia	32.2 (36.0–28.4)
Norway	31.9 (15.0–41.9)
Bosnia and Herzegovina	29.1 (25.0–32.1)
Turkey	23.1 (20.0–25.5)
Albania	17.3 (15.0–19.2)
Slovenia	14.8 (13.0–16.4)
Northern Macedonia	14.7 (13.0–16.2)
Lebanon	12.9 (11.0–14.1)
Latvia	9.7 (10.0–10.0)
Georgia	5.0 (4.0–5.4)
Luxembourg	3.3 (2.0–3.6)
Cyprus	2.3 (2.0–2.4)
Jordan	2.0 (2.0–2.2)

Numbers in parentheses represent the 95% confidence intervals to reflect associated uncertainty

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