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Estimating health and economic benefits of reductions in air pollution from agriculture

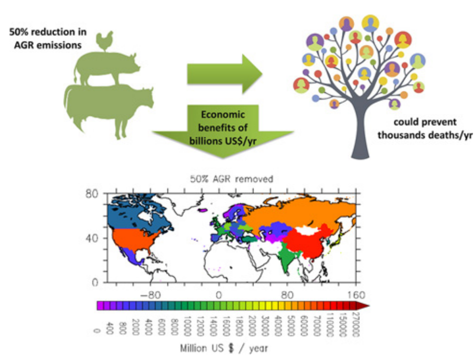
Despina Giannadaki [a,*], Elias Giannakis [a], Andrea Pozzer [b], Jos Lelieveld [a,b]

[a] The Cyprus Institute, Energy Environment and Water Research Center, P.O. Box 27456, 1645 Nicosia, Cyprus
[b] Max Planck Institute for Chemistry, Atmospheric Chemistry Department, Hahn-Meitnerweg 1, 55128 Mainz, Germany

HIGHLIGHTS

- Air pollution from agriculture imposes large health and economic burden to society.
- Apply the value of statistical life metric to monetize the related health outcomes.
- Reducing agricultural emissions by 50% leads to economic benefit of many billions US$.
- Ammonia abatement can generate positive economic and social benefits for the EU.

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural ammonia emissions strongly contribute to fine particulate air pollution ($PM_{2.5}$) with significant impacts on human health, contributing to mortality. We used model calculated emission scenarios to examine the health and economic benefits accrued by reducing agricultural emissions. We applied the "value of statistical life" metric to monetize the associated health outcomes. Our analysis indicates that a 50% reduction in agricultural emissions could prevent >200 thousand deaths per year in the 59 countries included in our study, notably in Europe, Russia, Turkey, the US, Canada and China, accompanied with economic benefits of many billions US$. In the European Union (EU) mortality could be reduced by 18% with an annual economic benefit of 89 billion US$. A theoretical complete phase-out of agricultural emissions could lead to a reduction in $PM_{2.5}$ related mortality of >50% plus associated economic costs in 42 out of the 59 countries studied. Within the EU, 140 thousand deaths could be prevented per year with an associated economic benefit of about 407 billion US$/year. A cost-benefit assessment of ammonia emission abatement options for the EU indicates that the reduction of agricultural emissions generates net financial and social benefits. The monetization of the health benefits of air pollution abatement policies and the costs of implementation can help devise cost-effective air quality management strategies.

1. Introduction

Air pollution by fine particulate matter ($PM_{2.5}$) has been recognized as the prime environmental health risk (Burnett et al., 2014; Cohen et al., 2005; Ezzati et al., 2002; Krewski et al., 2009; Lim et al., 2013;

* Corresponding author.
E-mail address: d.giannadaki@cyi.ac.cy (D. Giannadaki).

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Pope III et al., 2009; WHO, 2009). Outdoor $PM_{2.5}$ pollution is considered responsible for >3 million deaths annually (Lelieveld et al., 2015; Lim et al., 2013; WHO, 2014). Depending on their size, particles can penetrate deep into the lungs, and even reach the bloodstream and affect other organs. Apart from the concentration, the size and chemical composition can influence how hazardous $PM_{2.5}$ is for human health. However, information on the relationship between toxicity and chemical composition is very limited (Lippmann et al., 2013; Schneidemesser et al., 2016; Thurston et al., 2013; Tuomisto et al., 2008). Most fine particles originate from combustion processes in traffic, power plants, industry, household energy use, biomass burning, and from agriculture and natural sources. Fine particulates can cause health impacts even at very low concentrations (Pinault et al., 2016; Shi et al., 2015; WHO, 2006). Currently the European Union legislation poses a limit for annual mean $PM_{2.5}$ concentrations at 25 μg/m^3. The corresponding limit imposed by the U.S. Environmental Protection Agency is 12 μg/m^3, while the World Health Organization (WHO) ambient air quality guidelines suggest an annual mean $PM_{2.5}$ concentration threshold of 10 μg/m^3 (EPA, 2015; EU, 2008; WHO, 2006). Nevertheless, there is no clear evidence for a safe concentration limit below which health impacts can be fully prevented.

Air pollution also imposes economic cost to society for being responsible to mortality by a reduction in life expectancy (OECD, 2014; WHO ROE and OECD, 2015). The Organization for Economic Co-operation and Development (OECD) has estimated the economic value of deaths due to ambient air pollution at about US$3 trillion per year in its member countries, China and India. This corresponds to the amount that the population is willing to pay to avoid the deaths caused by air pollution with necessary interventions (OECD, 2014). In most OECD countries, the death toll from diseases caused by air pollution is much higher, typically by an order of magnitude, than by traffic accidents.

Recent studies reveal the significance of agriculture as an emission source that strongly contributes to fine particulate pollution (Bauer et al., 2016; Lelieveld et al., 2015; Pozzer et al., 2017). Lelieveld et al. (2015) and Lee et al. (2015) found that emission from agriculture is the largest relative contributor to $PM_{2.5}$ and the leading cause of mortality attributable to air pollution in Europe, Russia, the eastern United States, Canada and Japan. On a global scale one fifth of $PM_{2.5}$ related deaths could be avoided by eliminating emissions from agricultural activities (Lelieveld et al., 2015).

The main pollutant from agricultural activity is ammonia (NH_3), mainly from animal husbandry and its associated manure processing, and to a lesser extent from fertilizer use. Ammonia affects air quality through several multiphase chemical pathways, forming ammonium sulfate and ammonium nitrate, contributing to the overall particulate matter burden. The particles have an atmospheric lifetime of a few days to a week, and can be transported over great distances and influence human health and ecosystems on the regional scale. The contribution of ammonia emissions - almost exclusively coming from agriculture (~90%) - often represents 10–20% of fine particle mass in densely populated areas in Europe, and much higher in areas with intensive livestock farming, through secondary inorganic aerosol formation (EEA, 2015; Hendriks et al., 2013). Agriculture is also contributing to the air pollution burden through direct emissions of fine particles mainly from the combustion of agricultural waste or cropland burning, and through the emissions of tractors and other machines.

The aim of this work is to estimate the potential public health gains and economic benefits accrued by reducing agricultural (AGR) emissions in a number of countries in Europe, America and Asia. These valuations are based on sensitivity scenarios where agriculture emissions are reduced by 50%, 75% and 100%. Moreover, we present a cost and benefit assessment of selected ammonia emission abatement options, which have been investigated for the EU referring to the year 2010. Our findings indicate that the reduction of agricultural emissions generates net financial and social benefits for the EU despite the large emissions abatement costs.

2. Methods

2.1. Estimation of $PM_{2.5}$ related mortality

Health outcomes attributed to air pollution by $PM_{2.5}$ are associated mainly with cerebrovascular disease (CEV), ischaemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lung cancer (LC), and acute lower respiratory illness (ALRI) (Burnett et al., 2014; Lim et al., 2013). The mortality estimates presented in this work are based on the methodology used by Lelieveld et al. (2015). The health impact function in Eq. (1) was used in combination with exposure response function from Burnett et al. (2014) (Eq. (2)) and annual mean $PM_{2.5}$ concentrations simulated by the EMAC global atmospheric chemistry – climate model (Pozzer et al., 2012, 2017).

$$\Delta\mathrm{Mort} = y_o[(RR-1)/RR]\mathrm{Pop} \quad (1)$$

$$RR = 1 + a\{1 - \exp[-b(X-X_o)^p]\} \quad (2)$$

The mortality attributable to $PM_{2.5}$ (ΔMort) is a function of the baseline mortality rate y_o due to a particular disease category for countries and regions estimated by the World Health Organization (WHO, 2015). The term (RR-1)/RR is the attributable fraction of the disease burden and RR is the relative risk of the population (Pop) exposed to air pollution. Population data were obtained from the Columbia University Center for International Earth Science Information Network (CIESIN, 2014). The factor X is the annual mean total $PM_{2.5}$ concentration and X_o the background concentration below which no health impact is assumed. In this work, we assumed the same background limits of around 7.3 μg/m^3 depending on the disease category, adopted from Burnett et al. (2014). For details on the exposure response models for the five disease categories and related uncertainties we refer to Burnett et al. (2014) and Lelieveld et al. (2015) and references therein.

Recently, Pozzer et al. (2017) assessed the potential health benefits (i.e. decreased premature mortality) from reducing agricultural emissions. They used the same modeled annual mean $PM_{2.5}$ concentrations for the year 2010 as in Lelieveld et al. (2015) and Giannadaki et al. (2016) as reference simulation, obtained by the numerical global model EMAC, and performed three scenario simulations for the year 2010, reducing agricultural emissions in the model by 50%, 75% and 100% (Scenarios 1, 2 and 3, respectively). They investigated relatively large reductions of agricultural emissions to analyze the non-linear dependency of air pollution on these emissions. Smaller changes (e.g. by 10%) were investigated by Lee et al. (2015), which appear to less effectively contribute to $PM_{2.5}$ reduction per unit emission cutback.

EMAC contains sub-models that represent tropospheric and lower stratospheric processes and their interaction with oceans, land and human influences (Jöckel et al., 2006; Pozzer et al., 2012). Simulations were performed at T106 L31 resolution, which corresponds to a horizontal resolution of approximately 1.1° × 1.1° at the quadratic Gaussian grid (~100 × 100 km^2 at the equator), and 31 vertical levels up to 10 hPa in the lower stratosphere. For the model set-up they used anthropogenic emissions for the year 2010 from the EDGAR-CIRCE database (Emission Database for Global Atmospheric Research - Doering et al., 2009a, 2009b) and bulk natural aerosol emissions (i.e., desert dust and sea spray) based on prescribed data-sets for AEROCOM (Dentener et al., 2006). In these simulations the emissions for the year 2010 were used and the model results were evaluated against satellite based $PM_{2.5}$ estimates (Pozzer et al., 2017). The atmospheric chemistry is simulated with the MECCA module (Sander et al., 2011) and the aerosol microphysics and thermodynamics with the GMXe aerosol module (Pringle et al., 2010). The model meteorology has been forced by pre-calculated sea surface temperatures and ice coverage based on a 10-year climatology (Hurrell et al., 2008). Model evaluation based on in situ and remote sensing observations indicates that the seasonal distribution of aerosol optical depth is well represented by the model, and the model results largely agree with observed $PM_{2.5}$ concentrations. Extensive details about the model characteristics, the set-up, and model evaluation can be found in de Meij et al. (2012), Jöckel et al. (2006, 2010), Lelieveld et al. (2015), Pozzer et al. (2012, 2015, 2017) and Pringle et al. (2010).

In this study, we use the model simulations by Pozzer et al. (2017) to assess the economic cost of $PM_{2.5}$ related mortality and the potential economic benefits accrued by reductions of agricultural emissions.

2.2. Economic valuation of mortality

In the absence of a market for human lives, the monetization of mortality relies on non-market valuation methods, i.e., revealed or stated preference techniques (Bateman et al., 2002; Viscusi and Aldy, 2003). A standard method for estimating the monetary value of a positive welfare effect, e.g., a reduction in mortality risk, is to create a hypothetical market for the mortality risk considered and elicit individuals' willingness to pay (WTP) to reduce the risk of dying (Bateman et al., 2002; Braathen et al., 2010).

The Value of Statistical Life (VSL), the most established and widely used metric to monetize mortality risks associated to air pollution (OECD, 2012; WHO ROE and OECD, 2015), was applied in this study to assess the economic benefits of reducing emissions from agriculture. The VSL is defined as the marginal rate of substitution between wealth and mortality risk during a short time period, e.g., a year (Hammitt, 2000). It is not the value of any single person's life or death but it represents an aggregate of individuals' WTP to secure a marginal reduction in the risk of premature death. The VSL can be calculated with the following formula:

$$VSL = \frac{\partial WTP}{\partial R} \tag{3}$$

where R is the mortality risk; WTP is an individual's willingness to pay to reduce mortality risk by ΔR.

Ideally, the valuation of premature mortality costs across individual countries would require the use of empirically estimated VSLs for each of them. However, studies on WTP for mortality risk reduction are lacking in many countries (Narain and Sall, 2016). A unit value transfer approach was used here to assess the VSL of the individual countries considered in the study. More specifically, we used the VSL base value of \$3 million (in 2005-\$US) derived by the OECD (2012) meta-analysis study with recommended average VSL range at \$1.5 million–4.5 million. The findings of the meta-analysis study suggest that individuals in OECD countries are willing to pay US\$30 on average to reduce their risk of dying from air pollution by a margin of 1 in 100,000 (ΔR). Summing this average WTP value over 100,000 individuals gives a VSL equal to US\$3 million. Although this method assumes that individuals have similar tastes and characteristics for the study context between the countries, which thus yields a similar utility for marginal premature death risk reductions, it is still considered “as the simplest and most transparent way of transfer between countries” (Lindhjem and Navrud, 2015; OECD, 2012).

The VSLs for the individual countries (OECD, non-OECD European countries-see Table A4, China and India) were estimated for the year 2010 using the following formula (OECD, 2012), which captures the cross-sectional differences in income between countries and post-2005 economic growth:

$$VSL_{i,2010} = VSL_{OECD,2005} \times \left(\frac{Y_{i,2005}}{Y_{OECD,2005}}\right)^{\beta} \times (1 + \%\Delta P + \%\Delta Y)^{\beta} \tag{4}$$

where $VSL_{i,2010}$ is the adjusted VSL for country i in 2010; $VSL_{OECD,2005}$ is the base value of VSL for OECD countries in 2005; $Y_{i,2005}$ is the GDP per capita in country i in 2005 in PPP (purchasing power parity) terms; $Y_{OECD,2010}$ is the GDP per capita in OECD countries in 2005 in PPP terms; β is the income elasticity of the VSL equals to 0.8; $\%\Delta P$ represents price inflation; $\%\Delta Y$ represents post-2005 income growth. The calculations of VSL_i were conducted for 2010 in order to use the income elasticity suggested by the OECD (2012) study, that is, 0.8, thus avoiding uncertainties associated with the value of this parameter.

The *economic benefit* of reduced NH_3 emissions from agriculture in country i can be calculated by multiplying the estimated number of deaths attributable to air pollution that is avoided in country i (n_i) with the respective VSL value.

$$Economic\ benefit = (n_i) \times (VSL_i) \tag{5}$$

For the economic calculations we use upper and lower bounds based on the propagation of errors in n_i and VSL_i in Eq. (5).

Another metric, which applies to changes in life expectancy, is the Value of statistical Life Year (VOLY) (for detailed discussion of VSL and VOLY see Hammitt, 2007). However, no matter if VSL or VOLY metric is applied, the monetary costs related to annual mortality are in the range of billion euros in large cities (Sarigiannis et al., 2015), and over 1.5 trillion euros in OECD countries, China and India (OECD, 2014). The OECD, WHO, U.S. Environmental Protection Agency (EPA) and others have been applying the VSL method, whereas the European Commission (DG Environment) uses both the VSL and VOLY approaches (see, e.g., Holland, 2015).

We recognize considerable uncertainties in such a monetized valuation of reduced NH_3 from agriculture (plus health model uncertainties – see Lelieveld et al., 2015). The lack of data on WTP for reduced mortality risks, especially in low- and middle-income countries, increases the uncertainty in the estimation of VSL and thus in our effort to better understand the economic benefits of reducing air pollution, further emphasizing the need for conducting country-specific empirical studies on the WTP to reduce mortality risks. For more details on uncertainties in the estimates of VSL as well as uncertainties related to the adjustments required to reflect differences in population and risk context between different countries see Roman et al. (2012).

3. Results

3.1. Health and economic benefits

In previous work, Lelieveld et al. (2015) and Giannadaki et al. (2016) estimated premature mortality by CEV, IHD, COPD, LC and ALRI attributed to long-term exposure to $PM_{2.5}$ by applying annual mean concentrations of $PM_{2.5}$ for the year 2010, and using the risk function of Burnett et al. (2014). They estimated a global mortality attributable to $PM_{2.5}$ of 3.15 million (95% confidence interval (CI95): 1.52–4.60 million), with China and India being the leading countries with highest mortality due to $PM_{2.5}$ pollution (1.33 million; CI95: 0.64–1.94 million and 575 thousand; CI95: 277–840 thousand respectively). In the wider European region (Table A4), Russia and Ukraine rank high on the list (6th and 9th) with 67 thousand (CI95: 32–98 thousand) and 51 thousand respectively (CI95: 24–74 thousand), while for the European Union (EU-28) the estimate is about 173 thousand (CI95: 83–253 thousand) deaths, with Germany being the leading country in the ranking with 34 thousand (CI95: 16–50 thousand) per year. The United States (US) rank 7th in the global list with 52 thousand deaths in 2010 (CI95: 25–76 thousand).

Applying the mortality estimates to Eq. (5), using VSL obtained from Eq. (4) for the year 2010, we are able to estimate the economic cost of mortality due to $PM_{2.5}$ air pollution in countries with significant pollution levels (Table A1). The economic cost for each country is based on mortality levels and on the willingness to pay to reduce the risk for dying from air pollution, as described in the methods section. The economic cost for the 1.33 million deaths attributed to $PM_{2.5}$ pollution in China for the year 2010 is about 1.3 trillion US\$ (range (r): 0.39–2.2 trillion US\$), which corresponds to 966 US\$ per capita per year, which is

10% of the GDP per capita (data based on World Bank, 2017). In India the cost of about half million air pollution related deaths is about 346 billion US$ (r: 104–589 billion US$) or 299 US$ per capita per year (7% of GDP per capita). For the EU, our estimate is 504 billion US$ (r: 151–857 billion US$), which translates to about 1.05 thousand US$ per EU citizen, corresponding to 3% of GDP per capita, with Germany having the greater share of about 120 billion US$ or about 1.5 thousand US$ per capita (due to both high mortality and GDP), followed by Italy and France with a cost at about 59 and 56 billion US$, respectively (about 1.05 thousand and 924 US$ per capita) in 2010. In the wider European region, Russia has the highest mortality cost at 161 billion US$ (r: 48–273 billion US $; about 1.18 thousand per capita corresponding to 5.7% of GDP per capita) followed by Ukraine at 73 billion (r: 22–124 billion US$; 1.62 thousand per capita; 21% of GDP per capita) and Turkey at 62 billion US$ (r: 19–106 billion US$; 843 US$ per capita; 4.8% of GDP per capita). Our cost estimate for the US is 233 billion US$ (r: 70–396 billion US$) or 757 US$ per capita in 2010 corresponding to 1.7 of GDP per capita.

To assess the impact of emissions from agriculture on total $PM_{2.5}$ related mortality and the associated economic cost, we used the modeled sensitivity scenarios performed by Pozzer et al. (2017), where agricultural (AGR) emissions are reduced by 50%, 75% and 100%. Fig. 1 shows the annual premature mortality linked to $PM_{2.5}$ pollution for the countries considered in this study for the year 2010 (top left panel), and the respective rates under the three sensitivity scenarios.

Our analysis indicates that the impact of 50% reduced AGR emissions is relatively most significant in Estonia where mortality is reduced by 70% and in Finland, Norway and Canada with a reduction of >50% (Table 1). The economic cost follows the same percentage reduction as the mortality (Table A2), with the economic benefit being at a central value of 0.79 billion US$ in Estonia (r: 0.24–1.35 billion US$), 0.86 billion in Finland (r: 0.26–1.47 billion US$), 0.23 billion in Norway (r: 0.07–0.39 billion US$) and 5.5 billion US$ in Canada (r: 1.66–9.4 billion US$). In Russia and Ukraine, the countries with the highest health risk due to $PM_{2.5}$ in the wider European region, mortality and economic cost are reduced by 35% and 22%, respectively. In Russia, mortality is reduced from 67 thousand to 43 thousand deaths and the economic cost from 161 billion to 104 billion US$ in 2010 (57 billion US$ economic benefit with a range at 17–96 billion US$). In Ukraine, the 50% reduced AGR emissions scenario yields 11.5 thousand less deaths and a cost reduction of about 16 billion US$ (r: 4.9–28 billion US$). In the EU, mortality is reduced by 18% from 173 to 142 thousand deaths in 2010. We estimate the economic cost for EU citizens to be reduced by 89 billion US$ (r: 27–151 billion US$). In Germany, the country with the highest number of premature deaths in EU, mortality and economic cost are reduced by 14% (4.7 thousand less deaths and 16.5 billion US$ monetary benefit). Among the non-European countries with high $PM_{2.5}$ pollution, Japan has a significant reduction in mortality and economic cost by 34%, which is about 8 thousand less deaths and 25 billion US$ economic benefit (r: 7.4–42 billion US$). For the US we estimate a reduction in mortality and economic cost by 28% with 15 thousand less deaths and 66 billion US$ reduction in cost (r: 20–112 billion US$). In China and India, we estimate a relatively small reduction in mortality by 7 and 3%, respectively as the 50% reduced agricultural source does not strongly improve air quality. Nevertheless, even this relatively small percentage reduction can preclude >100 thousand air pollution related deaths in these countries (93 thousand in China, and 19 thousand in India) and reduce the economic cost by about 102 billion US$ in 2010 (r: 31–173 billion US$).

In the second sensitivity scenario, where AGR emissions are reduced by 75% the countries with a reduction in mortality and economic cost by

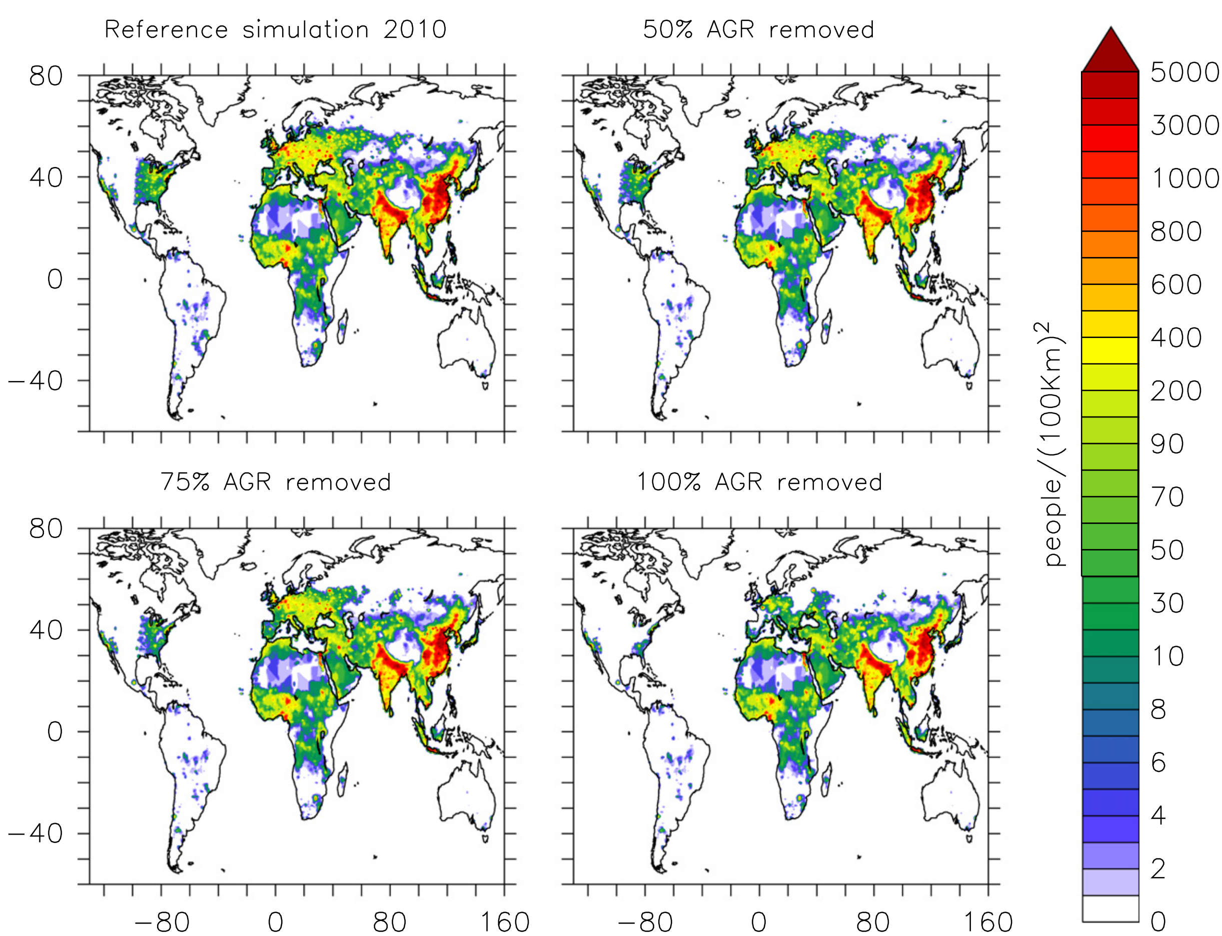

Fig. 1. $PM_{2.5}$ related mortality (in deaths/area of 100×100 km^2) for the year 2010 (top left, reference case) and the three sensitivity scenarios.

Table 1
Mortality attributed to $PM_{2.5}$ in 2010 and the corresponding mortality after the reduction in AGR emissions by 50, 75 and 100% for the countries with ≥20% reduction in mortality at 50% reduced AGR. In parenthesis the fractional reduction in %.

Country	Reference deaths ($\times 10^3$)	50% AGR removed deaths ($\times 10^3$)	75% AGR removed deaths ($\times 10^3$)	100% AGR removed deaths ($\times 10^3$)
Estonia	0.5	0.15 (70)	0.07 (86)	~0 (100)
Finland	0.45	0.19 (58)	0.06 (87)	~0 (100)
Norway	0.09	0.04 (56)	0.01 (89)	~0 (100)
Canada	2.99	1.48 (51)	0.53 (82)	0.01 (100)
Sweden	0.93	0.51 (45)	0.23 (75)	0.01 (99)
Latvia	1.27	0.77 (39)	0.25 (80)	0 (100)
Ireland	0.54	0.34 (37)	0.16 (70)	0.02 (96)
Russia	66.99	43.34 (35)	28.34 (58)	11.2 (83)
Japan	23.65	15.6 (34)	10.7 (55)	3.53 (85)
Belarus	7.73	5.49 (29)	2.48 (68)	~0 (100)
USA	51.75	37.06 (28)	25.47 (51)	14.66 (72)
Lithuania	2.15	1.56 (27)	0.68 (68)	~0 (100)
FYROM	0.63	0.46 (27)	0.37 (41)	0.16 (75)
Bulgaria	4.69	3.49 (26)	2.8 (40)	1.33 (72)
Georgia	1.39	1.05 (24)	0.91 (35)	0.37 (73)
Bosnia-Herzegovina	2.03	1.56 (23)	1.23 (39)	0.29 (86)
Ukraine	51.21	39.7 (22)	29.57 (42)	4.7 (91)
Serbia & Montenegro	5.43	4.22 (22)	3.22 (41)	0.89 (84)
Romania	14.61	11.37 (22)	8.64 (41)	2.03 (86)
Republic of Moldova	3.75	2.92 (22)	2.14 (43)	0.2 (95)
Slovenia	0.69	0.54 (22)	0.4 (42)	0.07 (90)
United Kingdom	15.47	12.15 (21)	8.27 (47)	1.12 (93)
Croatia	2.23	1.77 (21)	1.39 (38)	0.29 (87)
Switzerland	1.3	1.04 (20)	0.71 (45)	0.12 (91)
Denmark	1.61	1.29 (20)	0.98 (39)	0.08 (95)
France	17.57	14.08 (20)	10.64 (39)	3.58 (80)

50% and more are increased from four in scenario 1 to twelve. For six countries (Norway, Finland, Estonia, Canada and Latvia) the reduction is at 80% and higher. This additional 25% reduction in AGR would significantly benefit countries with high mortality rates in the wider European region like Russia and Ukraine with an additional reduction of mortality and economic cost by 23 and 20%, respectively, compared to the reduction in scenario 1. In the second scenario, 39 thousand deaths per year could be avoided in Russia (15 thousand more than with scenario 1), with an economic benefit of 93 billion US$ (r: 28–158 billion US$). In Ukraine, our estimate gives a potential reduction in mortality of 22 thousand (11 thousand more compared to scenario 1) with an economic benefit of about 31 billion US$ for 2010 (r: 9.2–52 billion US$). In the EU mortality and the associated cost are reduced by 36% (an additional 18% compared to scenario 1); 62 thousand deaths could be avoided and the economic cost could be reduced by 177 billion US$ (r: 53–302 billion US$). Germany will benefit with a 15% further reduction in mortality and cost per year. About 10 thousand deaths could be avoided with an economic benefit at 34 billion US$ (r: 10–58 billion US$). In the US, mortality and cost are reduced by half (an additional 23% less deaths compared to reduction in scenario 1) with an associated economic benefit at 118 billion US$ in 2010 (r: 35–201 billion US$). Mortality rates in Japan are also very sensitive to AGR emissions, with 55% less deaths in scenario 2 compared to 34% in scenario 1 and a reduction in the related cost by about 40 billion US$ per year (r: 12–67 billion US$). The above results show that even a small improvement in AGR emissions above the 50% abatement, would significantly reduce mortality and the related economic cost, because at 50% abatement the NH_3 limited regime for $PM_{2.5}$ formation is reached (Pozzer et al., 2017).

The last scenario, which represents a theoretical complete phase-out of AGR, leads to practically zero $PM_{2.5}$ related mortality in Belarus,

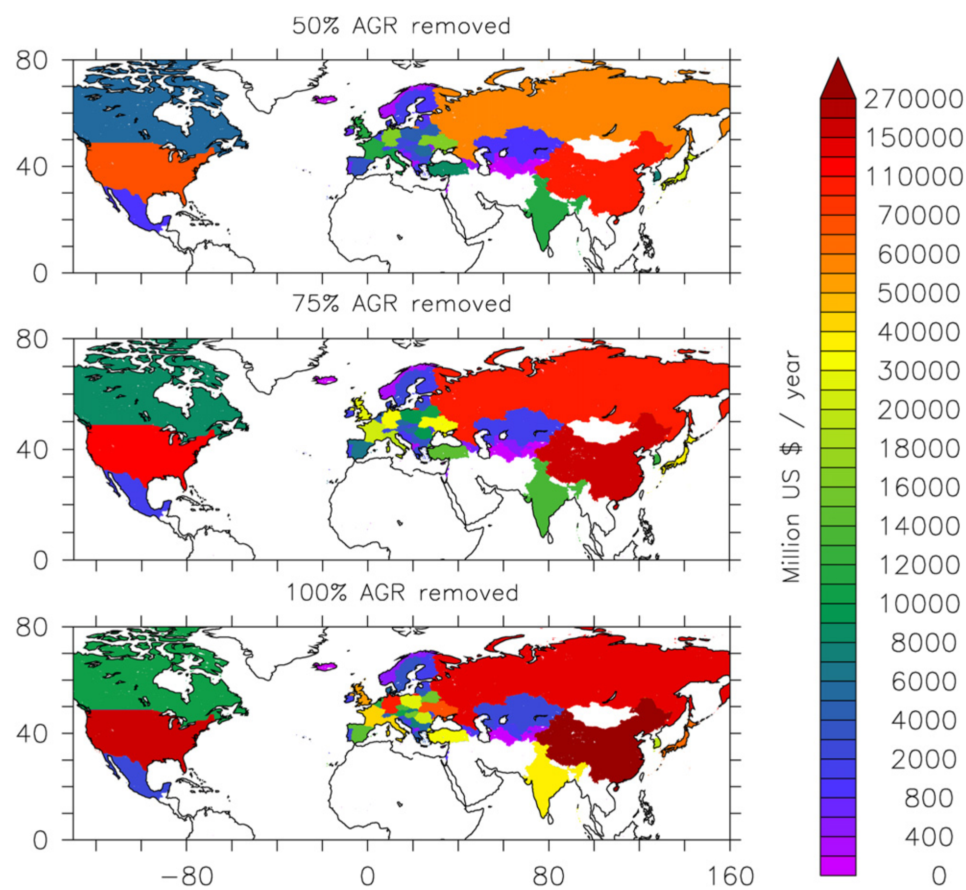

Fig. 2. Economic benefits of lowering $PM_{2.5}$ related mortality (in million US$ per year) from the three sensitivity scenarios with AGR emissions reduced by 50, 75 and 100% for the countries studied.

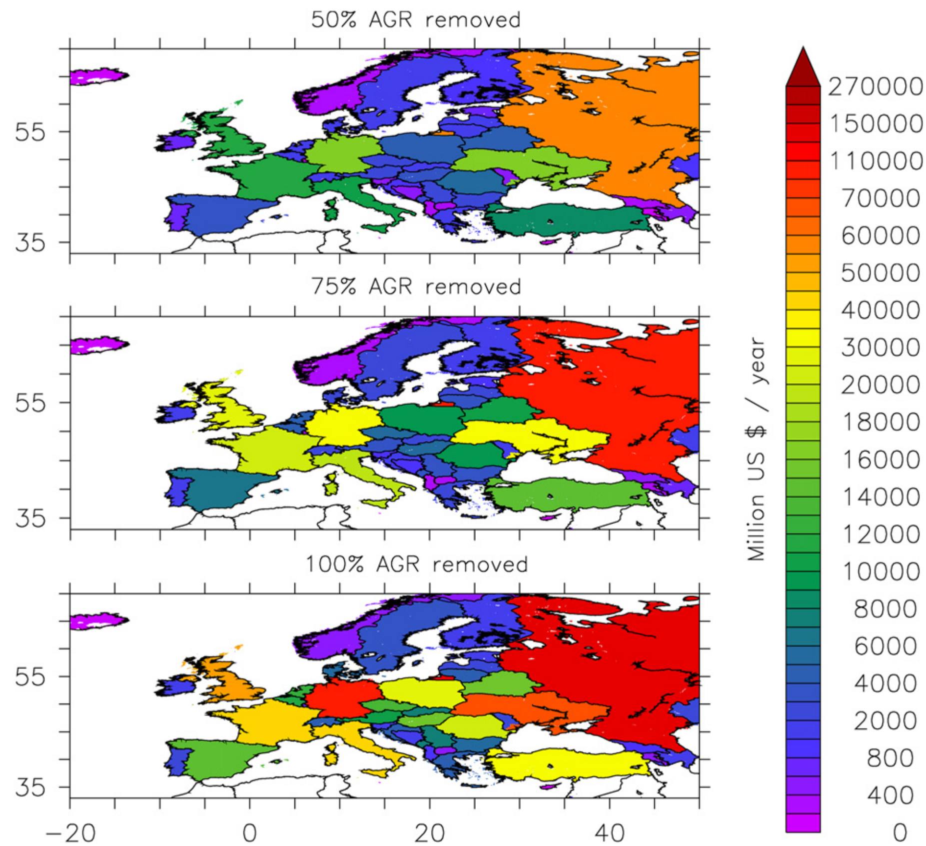

Fig. 3. Economic benefits of lowering $PM_{2.5}$ related mortality (in million US$ per year) from the three sensitivity scenarios with AGR emissions reduced by 50, 75 and 100% for the WHO_EUR region (see Table A4).

Table 2
Economic cost of mortality attributed to $PM_{2.5}$ in 2010 and the corresponding cost after the reduction in AGR emissions by 50, 75 and 100% for the EU-28 member countries.

Country	Reference cost US$ ($\times 10^6$)	50% AGR removed cost US$ ($\times 10^6$)	75% AGR removed cost US$ ($\times 10^6$)	100% AGR removed cost US$ ($\times 10^6$)
Germany	119,747	103,217	85,434	23,003
Italy	58,620	48,570	39,150	14,370
France	55,521	44,493	33,622	11,313
United Kingdom	54,919	43,133	29,359	3976
Romania	24,399	18,988	14,429	3390
Poland	30,576	25,683	20,622	4326
Hungary	16,495	13,479	11,043	1369
Spain	20,012	16,646	13,403	5906
Czech Republic	17,848	15,180	12,568	3960
Netherlands	17,710	15,717	12,822	5076
Bulgaria	8301	6177	4956	2354
Belgium	15,330	13,440	11,095	4165
Greece	10,913	9673	8742	6796
Slovakia	8857	7357	5953	1186
Austria	11,120	9102	7413	1028
Croatia	4616	3664	2877	600
Lithuania	4623	3354	1462	~0
Portugal	4625	3875	3375	2325
Denmark	5571	4463	3391	277
Latvia	2667	1617	525	~0
Sweden	3255	1785	805	35
Slovenia	2001	1566	1160	203
Ireland	2025	1275	600	75
Estonia	1135	341	159	~0
Finland	1494	631	199	~0
Malta	424	424	398	371
Cyprus	402	402	373	344
Luxembourg	691	565	440	63
Total	503,896	414,815	326,374	96,510

Lithuania, Latvia, Estonia, Finland, Norway, Canada and Sweden. In these countries, AGR is a key contributor to health risks by $PM_{2.5}$ (Table 1), thus elimination brings $PM_{2.5}$ levels below the threshold limit of accountable effect on human health, which is about 7.3 μg/m^3 annually averaged (Burnett et al., 2014). Overall, we count 42 countries with ≥50% reduction in mortality, compared to the reference case where we account for total $PM_{2.5}$. Russia and Ukraine, the countries with the highest mortality rates in the wider European region, experience a reduction of 83 and 91%, respectively. Mortality attributable to $PM_{2.5}$ in Russia is reduced from 67 thousand to 11 thousand deaths and the respective economic cost from 161 billion US$ to 27 billion US$ (central values). In the EU, mortality is reduced by 140 thousand in 2010 with an associated economic benefit of about 407 billion US$ (r: 122–692 billion US$), which corresponds to a reduction of about 81%. In Germany, Italy, France, UK, Romania and Poland, the EU countries with the relatively highest health impact, the reduction in mortality and cost range from 75% (Italy) to 93% (UK). The EU countries that are less affected by particulate pollution from AGR emissions are Greece (38% less deaths), Cyprus (14%) and Malta (13%). In the US, mortality is reduced from 52 thousand to 15 thousand (72% reduction) and the corresponding economic cost from 233 billion to 66 billion US$ - that is an economic benefit of 167 billion US$ in 2010 (r: 50–284 billion US$). In Japan mortality and economic cost are reduced by 85% leading to 20 thousand less deaths, with an economic benefit of 62 billion US$ (r: 18–105 billion US$). The elimination of AGR emissions in China and India, even though AGR does not strongly contribute to $PM_{2.5}$ levels and the corresponding mortality, could reduce mortality by 23 and 11%, respectively; hence > 370 thousand premature deaths would be avoided per year and the economic benefit would amount to about 342 billion US$ in 2010 (r: 103–582 billion US$).

Fig. 2 shows the annual economic benefits in million US$ accrued by the three scenarios of agricultural emissions reductions by 50, 75 and

100% respectively. Fig. 3 focuses on the WHO European region. Table 1 presents mortality estimates for the reference case and the three sensitivity scenarios for the countries with ≥20% reduction in mortality when AGR emissions are reduced by 50%. Table 2 presents the economic cost estimates for the reference simulation and the three sensitivity scenarios in EU countries. Tables A1 and A2 summarize the mortality and economic cost estimates for all countries considered in this study (49 countries of the WHO European region – see Table A4, the non-European OECD countries, China and India). The reduction in $PM_{2.5}$ levels from diminishing AGR emissions, leads to the same percent reduction in mortality and the associated economic cost. However, the ranking of countries with the higher monetized benefits does not follow that of countries with the higher health benefits, as the VSL of the individual countries is significantly affected by factors such as GDP per capita and the magnitude of risk reduction (Biausque, 2012).

We note also that we examined the potential impact of AGR emissions to $PM_{2.5}$ related mortality by assuming that all aerosol particles are equally toxic. The exposure response function relies on $PM_{2.5}$ mass concentrations, but it does not account for speciated emission sources, and the respective chemical composition and differential toxicity. Although there are studies that provide evidence of the role of different chemical composition on particle toxicity and the subsequent health outcomes (Lippmann et al., 2013; Thurston et al., 2013; Tuomisto et al., 2008) there are not sufficient data to support a comprehensive treatment of the toxicity factor in the health risk assessment (Brunekreef et al., 2015; Harrison and Yin, 2000; Reiss et al., 2007; Shiraiwa et al., 2012).

3.2. Cost-benefit assessment of emission abatement in the EU

The impact of agricultural emissions on $PM_{2.5}$ concentrations and the related burden of disease is an important challenge for the EU. Several ammonia emission abatement options have been explored to reduce the contribution of agriculture to air pollution and climate change (Klimont and Winiwarter, 2011, 2015; Oenema et al., 2007, 2012; Reis et al., 2015; UNECE, 2014; Wagner et al., 2011). Here, we present the costs and benefits of five selected NH_3 emission abatement options, which have been investigated for the EU referring to the year 2010, including low nitrogen feed, low emission animal housing, manure storage capacity (low efficiency), manure storage capacity (high efficiency) and techniques to reduce ammonia emission from fertilizers. The costs of the first four emission control measures (originally in €/kg N, converted to US$/kg N using the average exchange rate of the European Central Bank for 2010, that is, 1.326) apply to pig production (Table 3). However, similar cost ranges can be also considered for cattle production (Oenema et al., 2012).

Low nitrogen feed strategies to decrease ammonia emissions from pig production units usually include phase feeding and dietary changes towards an exchange of high-protein feed materials such as soybeans, by carbohydrate sources such as grain, and focus on (a) reducing urea concentration and excretion and (b) reducing ammonia production and volatilization during storage and application (van Vuuren et al., 2015). Low emission housing covers a number of options that prevent ammonia emissions from animal housing, basically reducing the surface area and exposure time of manure in the animal house. This includes flushing systems or other means of immediate transport of manure into storage (Klimont and Winiwarter, 2015). A summary of the calculated costs associated with ammonia reduction techniques in pig housing in Spain is presented in Montalvo et al. (2015). Techniques for reducing NH_3 emissions from stored manure include covers, storage design and manure processing. Most techniques are for liquid manure stores, whereas few methods are currently suited for solid manures (VanderZaag et al., 2015). High efficiency measures from manure storage capacity (e.g. using concrete, corrugated iron or polyester caps) can reduce NH_3 emissions up to 80%, while the other options (e.g., floating foils or polysterene) can reduce NH_3 emissions by 40% (Klimont and Winiwarter, 2015). Techniques to reduce ammonia

Table 3
Costs and benefits of ammonia emission abatement options for EU in 2010.

Ammonia emission abatement options	Cost of options *(US$/kg N removed[f])*	Ammonia emission abatement *(kg N removed)*	Total cost of options *(billion US$)*	Economic benefit from avoided deaths *(billion US$)*	Net economic benefit *(billion US$)*
Low nitrogen feed	0.66[a]	1,817,690, 000[d]	1.2	89.1[d]	87.9
Low emission animal housing	13.26[a]	1,817,690, 000[d]	24.1	89.1[d]	65.0
Manure storage capacity (low efficient measures)	2.65[b]	1,817,690, 000[d]	4.8	89.1[d]	84.3
Manure storage capacity (high efficient measures)	5.30[c]	2,726,540, 000[e]	14.5	177.5[e]	163
Fertilizers (urea application or substitution)	2.10[a]	1,817,690, 000[d]	3.8	89.1[d]	85.3

[a] The ammonia emission abatement options of low nitrogen feed, low emission housing and fertilizers can reduce total NH_3 emission in the EU by 10–20% with a maximum mitigation potential of 30% (source: Klimont and Winiwarter, 2015 and Oenema et al., 2012).
[b] Manure storage capacity leading to 40% ammonia emission reduction (source: Klimont and Winiwarter, 2015).
[c] Manure storage capacity leading to 80% ammonia emission reduction (source: Klimont and Winiwarter, 2015).
[d] Based on 50% reduction of agricultural emissions (scenario 1).
[e] Based on 75% reduction of agricultural emissions (scenario 2).
[f] Central values

emission from fertilizers include improved application of urea through appropriate timing and dose of application, or the substitution of urea by other chemical forms of fertilizers that are less easily releasing ammonia (Klimont and Winiwarter, 2015). Details about these NH_3 emission abatement options, the respective cost expressed in €/kg ammonia nitrogen removed (kg NH_3-N) and their efficiency are discussed in Klimont and Winiwarter (2015), Oenema et al. (2012) and in different chapters of Reis et al. (2015).

The estimated cost of NH_3 reduction for the different abatement options in EU is shown in Table 3. To evaluate the five abatement options we consider the total NH_3 removed in the EU (in kg NH_3-N) when AGR emissions are reduced by 50% and 75% (sensitivity scenarios 1 and 2) and the unit costs of the different measures. Although the 30% maximum potential reduction of NH_3 emissions from the options low nitrogen feed, low emission housing and fertilizers, and the economic benefit derived from our 50% reduction of agricultural emissions are not directly consistent, important indications can still be derived. The total cost for low nitrogen feed is estimated at a central value of 1.2 billion US$, for low emission animal housing at 24 billion US$, for fertilizer techniques at 3.8 billion US$ and for low efficient techniques for manure storage at 4.8 billion US$. The cost for the highly efficient techniques for manure storage is estimated at 14.5 billion US$ (based on 75% reduction in AGR emissions). The economic benefit from the avoided deaths in the EU in 2010 based on the two sensitivity scenarios (50% and 75% reduction in AGR emissions), which are close to the emissions reduction targets of the studied measures, is estimated at 89 and 177 billion US$, respectively. Our estimates indicate that the reduction of agriculture emissions generates a large net economic benefit for the EU under all selected abatement options. The largest net economic benefit results from the introduction of the highly efficient techniques for manure storage, being 163 billion US$. The findings of our cost and benefit assessment provide strong support for initiatives to strictly control NH_3 emissions from agricultural activities. We nevertheless recognize considerable uncertainties regarding assumptions about the estimation of costs and benefits of NH_3 control measures. However, such uncertainties are inevitable and need to be addressed in support of policies on agricultural emissions, as well as accompanying emission controls of other pollutants that contribute to ambient $PM_{2.5}$.

4. Discussion

Agricultural NH_3 emissions have a strong impact on $PM_{2.5}$ and related health outcomes, including mortality in Europe (mostly Northern and Northeastern Europe), Russia, Turkey, Japan, Canada and the US. As discussed in Pozzer et al. (2017), in Europe and East Asia ammonia concentrations must be decreased relatively more strongly than in North America and South Asia to reach the ammonia limited regime, i.e., after which additional emission reductions highly effectively decrease $PM_{2.5}$. The absolute reduction in $PM_{2.5}$ depends on the fraction of fine particulate mass that is directly NH_3 sensitive, which explains why strict NH_3 emission controls in Europe strongly affect $PM_{2.5}$ concentrations and the related health outcomes. The "jump" in effectiveness from 50 to 75% AGR emission reduction is related to the fact that at 50% reduction the ammonia limited regime is reached. The number of deaths each year related to the AGR source of air pollution (mainly release of ammonia) renders action to mitigate emissions imperative. The associated monetary values underscore the severity of the problem. Measuring the benefits of air pollution abatement policies, and comparing with costs of implementation can help devise cost-effective air quality management strategies.

The recent EU Directive 2016/2284 on the reduction of national emissions of certain atmospheric pollutants, which entered into force on 31 December 2016, sets national reduction commitments for sulfur dioxide, nitrogen oxides, volatile organic compounds, ammonia and fine particulate matter. For any year from 2020 to 2029, emissions of NH_3 across the EU need to be reduced by 6% (compared with 2005), while for any year from 2030 the reduction commitment is set at 19%. These reductions in NH_3 emissions are not very stringent, especially when compared to the reduction commitments of sulfur dioxide (by 59% for 2020, 79% for 2030) and nitrogen oxides (42% by 2020, 63% by 2030), and also considering the efficiency of NH_3 emission reduction in reducing $PM_{2.5}$. Abatement of ammonia is a key factor in reducing aerosol formation, and it is relatively more effective in achieving $PM_{2.5}$ reductions compared to the abatement of sulfur and nitrogen oxides (Brunekreef et al., 2015; Megaritis et al., 2013; Tsimpidi et al., 2007). Therefore, all precursor gases should be reduced at least equivalently to achieve the maximum potential reduction in $PM_{2.5}$ concentrations.

The Common Agricultural Policy (CAP) with an annual budget of 52 billion € in 2015 (2011 constant prices), that is, 39% of the total EU budget (European Commission, 2017) in conjunction with the current environmental directives could provide the instruments and conditions for a spatial optimization of agricultural production in the EU (Van Grinsven et al., 2013; Giannakis and Bruggeman, 2015). Various environmental policy measures have been implemented from the early 1990s onwards to reduce the environmental impact of agricultural ammonia emissions, but the success has been limited. The lack of integration of the available measures and the lack of enforcement contribute to the inadequacy of measures (Oenema et al., 2009). The order of implementation of the measures is also important; for example, NH_3 emission abatement measures should be implemented together with integrated N management (Oenema et al., 2009). Schucht et al. (2015) note that the enforcement of current European air quality policies, and the move towards stringent climate policies on a global scale, can lead to reduced health impacts and air pollution cost savings in Europe. Thus, a stronger integration of the agricultural policies with the environmental and climate policies is necessary to respond to the environmental challenges. The subsequent reforms of the CAP move towards this direction. More precisely, the mid-term review of CAP in 2003 introduced the cross-compliance regime, which links direct payments to environmental protection, food safety, animal health and welfare standards as well as the requirement of maintaining land in good agricultural and environmental conditions (Council Regulation (EC) No 1782/2003). The 2013 CAP reform further enhanced the environmental performance of European agriculture through the mandatory 'greening' of direct payments, which accounts for 30% of the national direct payments, and supports agricultural practices beneficial for the environment and the climate, such as crop diversification, maintenance of permanent grass and establishment of ecological focus areas (EU Regulation 1307/2013). However, a simplification of the management and control system processes is required to increase the effectiveness of those compulsory environmentally-friendly practices (European Court of Auditors, 2016).

Although the adverse health outcomes and the associated economic burden to society of agricultural emissions are far greater than is the burden placed on the agricultural sector in Europe by the current proposal for national emission ceilings (Brunekreef et al., 2015), the costs of the agricultural emission abatement options are substantial and may affect the competitiveness of the agricultural sector. It should be also noted that, due to economies of scale, some of the abatement techniques may be more cost-effective on large farms than on small farms (UNECE, 2014). Considering that the implementation of agricultural emission abatement options is a large cost factor, and the fact that CAP mechanisms do not allow direct subsidies of agricultural production, different financial compensation schemes linked to environmental protection, i.e., an enhanced cross-compliance may need to be designed to transfer part of the societal benefits of reduced agricultural emissions back to the farmers. Mitigation measures on the demand-side of certain agricultural products can also offer great potential for meeting the challenges of ammonia emissions abatement. The consumption rate of animal-based food products by humans negatively affects NH_3 emissions, thus shifts in diets towards plant-based foods can have a large impact on NH_3 emissions per person. Sheppard and Bittman (2015) estimated that from 1981 to 2006 the per person protein intake in the Canadian diet increased about 5%, but NH_3 emission related to that diet decreased 20% mainly due to reduced consumption of beef. Levying taxes on the consumption side of emissions-intensive food commodities such as meat and dairy could foster the change towards more balanced diets, which could positively affect agricultural emissions (Springmann et al., 2017). Overall, a mix of supply and demand-side measures can offer great potential for meeting the goal of mitigating greenhouse gas and ammonia emissions from agriculture (Smith et al., 2013).

5. Conclusions

Using estimates of premature mortality attributable to $PM_{2.5}$ pollution, this study estimates the associated economic costs by using the VSL metric that monetizes the increased premature mortality risk from air pollution according to individuals' willingness to pay. We focused on the impacts of agricultural emissions – mainly NH_3 releases – to $PM_{2.5}$ related mortality and the associated economic cost to society. To examine the potential health and economic benefits we used three sensitivity scenarios where agricultural emissions were reduced by 50, 75 and 100%.

The results of the study highlight the magnitude of the health and economic benefits to societies that can be achieved by ammonia emission management. The economic benefits from reducing premature death risks attributable to agricultural emissions are estimated to amount to many billions of dollars in various countries. Increasing the awareness of the role of agriculture as a major contributor to particulate matter concentrations and the relevant health and economic implications is crucial for the societal acceptance of mitigation action, and designing and enforcing abatement policy measures.

The positive economic and social benefit for the European society estimated in this study is considered a lower limit in view of the overall benefits of reducing agricultural emissions, i.e., environmental protection and sustainability of agriculture, and reinforce the need for action.

Competing interests

The authors declare that they have no competing interests.

Appendix A

Table A1
Mortality attributed to $PM_{2.5}$ in 2010 and the corresponding mortality after the reduction in AGR emissions by 50, 75 and 100% for the 59 countries studied. In parenthesis the fractional reduction in %.

Country	Reference deaths ($\times 10^3$)	50% AGR removed deaths ($\times 10^3$)	75% AGR removed deaths ($\times 10^3$)	100% AGR removed deaths ($\times 10^3$)
China	1327.13	1234.51 (7)	1162.29 (12)	1016.53 (23)
India	575.30	555.84 (3)	553.24 (4)	509.83 (11)
Russia	66.99	43.34 (35)	28.34 (58)	11.2 (83)
USA	51.75	37.06 (28)	25.47 (51)	14.66 (72)
Ukraine	51.21	39.7 (22)	29.57 (42)	4.7 (91)
Germany	34.41	29.66 (14)	24.55 (29)	6.61 (81)
Turkey	30.92	26.65 (14)	23.82 (23)	15.78 (49)
Japan	23.65	15.6 (34)	10.7 (55)	3.53 (85)
Italy	19.54	16.19 (17)	13.05 (33)	4.79 (75)
France	17.57	14.08 (20)	10.64 (39)	3.58 (80)
United Kingdom	15.47	12.15 (21)	8.27 (47)	1.12 (93)
Romania	14.61	11.37 (22)	8.64 (41)	2.03 (86)
Poland	14.56	12.23 (16)	9.82 (33)	2.06 (86)
Korea	14.27	11.92 (16)	10.25 (28)	7.91 (45)
Uzbekistan	11.2	10.44 (7)	9.94 (11)	8.55 (24)
Belarus	7.73	5.49 (29)	2.48 (68)	~0 (100)
Hungary	7.11	5.81 (18)	4.76 (33)	0.59 (92)
Spain	6.54	5.44 (17)	4.38 (33)	1.93 (70)
Czech Republic	6.49	5.52 (15)	4.57 (30)	1.44 (78)
Serbia & Montenegro	5.43	4.22 (22)	3.22 (41)	0.89 (84)
Netherlands	4.71	4.18 (11)	3.41 (28)	1.35 (71)
Bulgaria	4.69	3.49 (26)	2.8 (40)	1.33 (72)
Belgium	4.38	3.84 (12)	3.17 (28)	1.19 (73)
Turkmenistan	4.04	4.01 (1)	4 (1)	3.92 (3)
Greece	3.87	3.43 (11)	3.1 (20)	2.41 (38)
Republic of Moldova	3.75	2.92 (22)	2.14 (43)	0.2 (95)
Slovakia	3.66	3.04 (17)	2.46 (33)	0.49 (87)
Kazakhstan	3.64	3.1 (15)	2.84 (22)	2.45 (33)
Azerbaijan	3.05	2.76 (10)	2.54 (17)	2.08 (32)
Austria	3.03	2.48 (18)	2.02 (33)	0.28 (91)
Canada	2.99	1.48 (51)	0.53 (82)	0.01 (100)
Mexico	2.66	2.15 (19)	1.63 (39)	1.01 (62)
Croatia	2.23	1.77 (21)	1.39 (38)	0.29 (87)
Lithuania	2.15	1.56 (27)	0.68 (68)	~0 (100)
Israel	2.03	1.93 (5)	1.88 (7)	1.75 (14)
Bosnia-Herzegovina	2.03	1.56 (23)	1.23 (39)	0.29 (86)
Kyrgyz Republic	1.91	1.78 (7)	1.69 (12)	1.47 (23)
Portugal	1.85	1.55 (16)	1.35 (27)	0.93 (50)
Denmark	1.61	1.29 (20)	0.98 (39)	0.08 (95)
Chile	1.43	1.23 (14)	1.04 (27)	0.7 (51)
Tajikistan	1.39	1.24 (11)	1.19 (14)	1 (28)
Georgia	1.39	1.05 (24)	0.91 (35)	0.37 (73)
Albania	1.36	1.14 (16)	1.01 (26)	0.6 (56)
Switzerland	1.3	1.04 (20)	0.71 (45)	0.12 (91)
Latvia	1.27	0.77 (39)	0.25 (80)	~0 (100)
Armenia	1.06	0.91 (14)	0.81 (24)	0.37 (65)
Sweden	0.93	0.51 (45)	0.23 (75)	0.01 (99)
Australia	0.84	0.73 (13)	0.73 (13)	0.69 (18)

Table A1 (*continued*)

Country	Reference deaths ($\times 10^3$)	50% AGR removed deaths ($\times 10^3$)	75% AGR removed deaths ($\times 10^3$)	100% AGR removed deaths ($\times 10^3$)
Slovenia	0.69	0.54 (22)	0.4 (42)	0.07 (90)
FYROM	0.63	0.46 (27)	0.37 (41)	0.16 (75)
Ireland	0.54	0.34 (37)	0.16 (70)	0.02 (96)
Estonia	0.5	0.15 (70)	0.07 (86)	~0 (100)
Finland	0.45	0.19 (58)	0.06 (87)	~0 (100)
Malta	0.16	0.16 (0)	0.15 (6)	0.14 (13)
Cyprus	0.14	0.14 (0)	0.13 (7)	0.12 (14)
Luxembourg	0.11	0.09 (18)	0.07 (36)	0.01 (91)
Norway	0.09	0.04 (56)	0.01 (89)	~0 (100)
New Zealand	0	0 (0)	0 (0)	0 (0)
Iceland	0	0 (0)	0 (0)	0 (0)

Table A2
Economic cost of mortality attributed to $PM_{2.5}$ in 2010 and the corresponding cost after the reduction in AGR emissions by 50, 75 and 100% for the 59 countries studied.

Country	Reference cost US$ ($\times 10^6$)	50% AGR removed cost US$ ($\times 10^6$)	75% AGR removed cost US$ ($\times 10^6$)	100% AGR removed cost US$ ($\times 10^6$)
China	1,293,952	1,203,647	1,133,233	991,117
India	346,331	334,616	333,050	306,918
Russia	160,776	104,016	68,016	26,880
USA	232,772	166,696	114,564	65,941
Ukraine	72,718	56,374	41,989	6674
Germany	119,747	103,217	85,434	23,003
Turkey	62,458	53,833	48,116	31,876
Japan	72,558	47,861	32,828	10,830
Italy	58,620	48,570	39,150	14,370
France	55,521	44,493	33,622	11,313
United Kingdom	54,919	43,133	29,359	3976
Romania	24,399	18,988	14,429	3390
Poland	30,576	25,683	20,622	4326
Korea	43,195	36,082	31,027	23,944
Uzbekistan	4928	4594	4374	3762
Belarus	15,537	11,035	4985	0
Hungary	16,495	13,479	11,043	1369
Spain	20,012	16,646	13,403	5906
Czech Republic	17,848	15,180	12,568	3960
Serbia & Montenegro	9503	7385	5635	1558
Netherlands	17,710	15,717	12,822	5076
Bulgaria	8301	6177	4956	2354
Belgium	15,330	13,440	11,095	4165
Turkmenistan	3919	3890	3880	3802
Greece	10,913	9673	8742	6796
Republic of Moldova	2363	1840	1348	126
Slovakia	8857	7357	5953	1186
Kazakhstan	6734	5735	5254	4533
Azerbaijan	4423	4002	3683	3016
Austria	11,120	9102	7413	1028
Canada	10,934	5412	1938	37
Mexico	4817	3894	2952	1829
Croatia	4616	3664	2877	600
Lithuania	4623	3354	1462	0
Israel	5928	5636	5490	5110
Bosnia-Herzegovina	2152	1654	1304	307
Kyrgyz Republic	936	872	828	720
Portugal	4625	3875	3375	2325
Denmark	5571	4463	3391	277
Chile	2750	2365	2000	1346
Tajikistan	612	546	524	440
Georgia	1168	882	764	311
Albania	1510	1265	1121	666
Switzerland	5005	4004	2734	462
Latvia	2667	1617	525	0
Armenia	880	755	672	307
Sweden	3255	1785	805	35
Australia	3297	2865	2865	2708
Slovenia	2001	1566	1160	203
FYROM	794	580	466	202
Ireland	2025	1275	600	75
Estonia	1135	341	159	0
Finland	1494	631	199	0
Malta	424	424	398	371

(continued on next page)

Table A2 (*continued*)

Country	Reference cost US$ ($\times 10^6$)	50% AGR removed cost US$ ($\times 10^6$)	75% AGR removed cost US$ ($\times 10^6$)	100% AGR removed cost US$ ($\times 10^6$)
Cyprus	402	402	373	344
Luxembourg	691	565	440	63
Norway	419	186	47	0
New Zealand	0	0	0	0
Iceland	0	0	0	0

Table A3
Values for VSL in 2010 for the countries studied.

Country	VSL in 2010[a] (million US$)
Albania	1.11
Armenia	0.83
Australia	3.93
Austria	3.67
Azerbaijan	1.45
Belarus	2.01
Belgium	3.50
Bosnia-Herzegovina	1.06
Bulgaria	1.77
Canada	3.66
Chile	1.92
China	0.98
Croatia	2.07
Cyprus	2.87
Czech Republic	2.75
Denmark	3.46
Estonia	2.27
Finland	3.32
France	3.16
FYROM	1.26
Georgia	0.84
Germany	3.48
Greece	2.82
Hungary	2.32
Iceland	4.46
India	0.60
Ireland	3.75
Israel	2.92
Italy	3.00
Japan	3.07
Kazakhstan	1.85
Korea	3.03
Kyrgyz Republic	0.49
Latvia	2.10
Lithuania	2.15
Luxembourg	6.28
Malta	2.65
Mexico	1.81
Netherlands	3.76
New Zealand	2.94
Norway	4.65
Poland	2.10
Portugal	2.50
Republic of Moldova	0.63
Romania	1.67
Russia	2.40
Serbia and Montenegro	1.75
Slovakia	2.42
Slovenia	2.90
Spain	3.06
Sweden	3.50
Switzerland	3.85
Tajikistan	0.44
Turkey	2.02
Turkmenistan	0.97
Ukraine	1.42
United Kingdom	3.55
United States of America	4.50
Uzbekistan	0.44

[a] With OECD base value of 3 million US$ in 2005, adjusted for differences in per capita GDP at PPP with an income elasticity to the power of 0.8, and adjusted for post-2005 income growth and inflation. Source: OECD, 2014.

Table A4
WHO European region: mortality strata, child and adult mortality characteristics, and the countries included.

Stratum	Child mortality	Adult mortality	Countries within stratum
EUR-A	Very low	Very low	Austria, Belgium, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Slovenia, Spain, Sweden, Switzerland, United Kingdom
EUR-B	Low	Low	Albania, Armenia, Azerbaijan, Bosnia & Herzegovina, Bulgaria, Georgia, Kyrgyzstan, Poland, Romania, Serbia & Montenegro, Slovakia, Tajikistan, FYROM, Turkey, Turkmenistan, Uzbekistan
EUR-C	Low	High	Belarus, Estonia, Hungary, Kazakhstan, Latvia, Lithuania, Republic of Moldova, Russia, Ukraine

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