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Ammonia Emission Controls as a Cost-Effective Strategy for Reducing Atmospheric Particulate Matter in the Eastern United States

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Current regulation aimed at reducing inorganic atmospheric fine particulate matter ($PM_{2.5}$) is focused on reductions in sulfur dioxide (SO_2) and oxides of nitrogen ($NO_x \equiv NO + NO_2$); however, controls on these pollutants are likely to increase in cost and decrease in effectiveness in the future. A supplementary strategy is reduction in ammonia (NH_3) emissions, yet an evaluation of controls on ammonia has been limited by uncertainties in emission levels and in the cost of control technologies. We use state of the science emission inventories, an emission-based regional air quality model, and an explicit treatment of uncertainty to estimate the cost-effectiveness and uncertainty of ammonia emission reductions on inorganic particulate matter in the Eastern United States. Since a paucity of data on agricultural operations precludes a direct calculation of the costs of ammonia control, we calculate the "ammonia savings potential", defined as the minimum cost of applying SO_2 and NO_x emission controls in order to achieve the same reduction in ambient inorganic $PM_{2.5}$ concentration as obtained from a 1 ton decrease in ammonia emissions. Using 250 scenarios of NH_3, SO_2, and NO_x emission reductions, we calculate the least-cost SO_2 and NO_x control scenarios that achieve the same reduction in ambient inorganic $PM_{2.5}$ concentration as a decrease in ammonia emissions. We find that the lower-bound ammonia savings potential in the winter is \$8,000 per ton NH_3; therefore, many currently available ammonia control technologies are cost-effective compared to current controls on SO_2 and NO_x sources. Larger reductions in winter inorganic particulate matter are available at lower cost through controls on ammonia emissions.

1. Introduction

One of the more pernicious problems in air quality is the persistence of fine suspended particulate matter. Recent regulation has focused on controlling $PM_{2.5}$, which refers to particles with diameter less than 2.5 micrometers. These particles are statistically associated with increased incidence of pulmonary disease and reduced lung function (*1*, *2*), cardiac arrest (*3*−*5*), and premature death (*6*, *7*). The deposition of these particles degrades sensitive terrestrial and aquatic ecosystems (*8*, *9*), and due to their light scattering properties, these particles impair visibility at scenic vistas (*10*) and contribute to climate change (*11*).

In the Eastern United States, approximately half of the $PM_{2.5}$ has an inorganic chemical speciation and is composed of ammonium (NH_4^+), nitrate (NO_3^-), and sulfate (SO_4^{2-}) (*12*). Very little of the inorganic $PM_{2.5}$ is attributable to direct emissions. Emissions of oxides of nitrogen ($NO_x \equiv NO + NO_2$) and sulfur dioxide (SO_2), mostly from combustion sources, are oxidized in the atmosphere to form nitric acid (HNO_3) and sulfuric acid (H_2SO_4), respectively. These species partition between the gas phase and particle phase in an effort to establish thermodynamic equilibrium (*13*). H_2SO_4 has a low vapor pressure such that sulfate occurs overwhelmingly in the particle phase. Ammonia (NH_3) can neutralize the H_2SO_4 to form ammonium sulfate ($(NH_4)_2SO_4$) or ammonium bisulfate (NH_4HSO_4). Also, NH_3 can neutralize the gas-phase HNO_3 to form ammonium nitrate (NH_4NO_3) aerosol. The phase partitioning of ammonium nitrate is dependent on the temperature, relative humidity, and concentration of NH_3, NH_4^+, SO_4^{2-}, HNO_3, and NO_3^-. Although NH_4^+ by itself is a small fraction of the $PM_{2.5}$ mass, NH_3 plays a disproportionate role by determining the phase state of HNO_3 and the neutralization state of H_2SO_4.

The U.S. Environmental Protection Agency has established an ambient standard for $PM_{2.5}$ as 15 $\mu g\ m^{-3}$ on an annual average basis. Over 90 million people live in non-attainment areas that exceed this standard (*14*). Recent national efforts intended to reduce inorganic $PM_{2.5}$ concentrations, such as the Clean Air Interstate Rule, focus only on SO_2 and NO_x emission reductions, despite the important role of NH_3. Historically, the sources of NO_x and SO_2 were obvious, easy to control, and effective at reducing $PM_{2.5}$ (*15*). NH_3 emissions are largely from animal excreta at livestock operations and chemical fertilizer applied to crops (*16*). These sources are difficult to quantify and preclude the use of typical control options.

Continued reductions in NO_x and SO_2 emissions are likely to cost more than in the past (*17*, *18*) and may be less effective at reducing $PM_{2.5}$ (*19*, *20*) than reductions in ammonia emissions. Reductions in SO_4^{2-} increase the available NH_3, and a portion of this free NH_3 partitions to the aerosol phase as NH_4NO_3. Hence, a portion of the SO_4^{2-} is replaced by NO_3^-, which reduces the effectiveness of SO_2 controls. NO_x controls are effective only if the formation of NH_4NO_3 is limited by the nitric acid concentration rather than the available ammonia concentration.

Recent research has improved ammonia emission estimates (*21*−*23*) and control options for NH_3 emissions are better understood and more feasible (*24*). In short, it is time to re-evaluate the potential for NH_3 emission reductions as a cost-effective control strategy for $PM_{2.5}$.

In this study, we present a coupled analysis of the costs of pollutant controls and the effectiveness of emission reductions to determine if ammonia emission reductions are a cost-effective control strategy for reducing ambient inorganic $PM_{2.5}$ concentrations. A "control strategy" is a combination of NH_3, NO_x, and SO_2 emission reductions applied across the domain of interest (the Eastern United States). By "effectiveness", we are referring to the impact of the control strategy on the ambient inorganic $PM_{2.5}$ concentration. A control strategy is the most cost-effective if

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there is no other control strategy that results in a larger reduction in the ambient inorganic $PM_{2.5}$ concentration at a lower cost.

Although many robust ammonia emission control technologies exist, the extent to which they can be deployed in the Eastern United States is uncertain due to a scarcity of farming practices data. Rather than directly calculate the cost-effectiveness of ammonia emission controls; instead, we calculate the "ammonia savings potential" (units of \$ ton^{-1} NH_3 emission reduction). Every ton of ammonia emission reduction causes a decrease in the ambient inorganic $PM_{2.5}$ concentration, as less ammonia is available to form ammonium nitrate and ammonium sulfate. The same reduction in ambient inorganic $PM_{2.5}$ could be achieved by controlling SO_2 and NO_x sources. The ammonia savings potential is the minimum cost of controls on SO_2 and NO_x sources that would be needed to achieve the same ambient inorganic $PM_{2.5}$ reduction as a 1 ton reduction of ammonia emissions. The ammonia savings potential provides a basis for comparing the costs of ammonia emission reductions with those of SO_2 and NO_x controls. If a given ammonia emission control technology, such as reduced fertilizer application or covered manure storage, has costs (\$ ton^{-1} NH_3 emission reduction) less than the ammonia savings potential, then that control technology is more cost-effective for reducing ambient inorganic $PM_{2.5}$ than controls on SO_2 and NO_x sources. We use this approach to estimate the cost-effectiveness of ammonia emission controls for the United States east of the Rocky Mountains during summer and winter conditions.

2. Methods

In this section we describe the method for calculating the effectiveness (% change in ambient inorganic $PM_{2.5}$ concentration), cost (\$), and ammonia savings potential (\$ ton^{-1} of NH_3 emission reduction).

2.1 Effectiveness Calculation. The effectiveness of an emission control strategy is the change in inorganic $PM_{2.5}$ concentration compared with current inorganic $PM_{2.5}$ concentrations under present day emissions. We estimate the effectiveness using $PMCAM_x$, an Eulerian chemical transport model of regional air quality (*25*−*27*). $PMCAM_x$ predicts the change in species concentration due to emissions, advection, dispersion, gas-phase and aqueous-phase chemistry, aerosol processes (coagulation, condensation, and nucleation), and wet and dry deposition.

Emissions inputs of NO_x, SO_2, volatile organic compounds (VOCs) species, and carbonaceous aerosols are from the LADCO BaseE inventory, generated using EMS-2003 (*28*). The LADCO inventory is derived primarily from the U.S. EPA's National Emission Inventory 1999 version 2.0 (*29*). Emissions of NH_3 are from a temporally resolved, process-based inventory described in Pinder et al. (*30*). Temperature, wind fields, rainfall, and other meteorological inputs are from the MM5 meteorological model (*31*).

The model domain includes the central and eastern United States, ranging from west Texas to Maine. A map of the model domain can be found in the Supporting Information. The domain is divided into a 36 × 36 km grid with 16 vertical layers. A complete evaluation of this configuration of $PMCAM_x$ using national monitoring networks and detailed data from the Pittsburgh Air Quality Study (*27*, *30*) has shown that the model adequately captures the spatial and temporal variations of inorganic $PM_{2.5}$. A comparison with the SEARCH network can be found in the Supporting Information.

The U.S. EPA designates regions that have annual average $PM_{2.5}$ concentrations in excess of 15 $\mu g\ m^{-3}$ as "non-attainment areas" (*14*). The grid cells in non-attainment with similar sensitivity to emission changes are grouped together

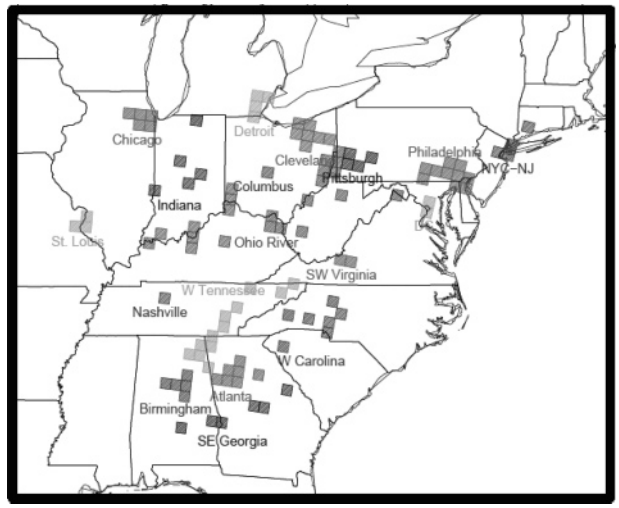

FIGURE 1. $PMCAM_x$ grid cells used to calculate effectiveness of emission controls in non-attainment areas.

and are shown in Figure 1. When calculating the effectiveness, we include only the surface grid cells at these locations.

We begin by developing an emission scenario for every combination of pollutant (SO_2, NO_x, NH_3) and emission reduction percent (0%, 10%, 20%, 30%, and 50%), thereby yielding 125 scenarios. For each scenario, emissions are reduced in a uniform manner by applying a constant factor to all sources across space and time. Future work should address control strategies specific to source sectors or time periods.

With each scenario emission inventory, $PMCAM_x$ is executed for two, 2-week time periods: July 12−25, 2001 and January 9−22, 2002. These time periods are representative of typical summer and winter conditions. They begin with low pollutant concentrations; near the middle of the simulation there is a stationary system which creates high concentrations, until the pollutants are transported east by a low-pressure system. These time periods were selected such that the effect of emission controls on both average and episodic conditions can be estimated. The computational requirements (250 CPU weeks) preclude modeling longer time periods. The first 3 days of the simulated period are discarded to avoid sensitivity to initial conditions.

We then calculate the $PMCAM_x$ predicted inorganic $PM_{2.5}$ as the sum of particle phase NH_4^+, NO_3^-, and SO_4^{2-} concentrations for particles with diameter less than 2.5 μm. This value is averaged over the simulation time for all surface grid cells marked in Figure 1. The effectiveness is then the percent change in inorganic $PM_{2.5}$ concentration from the base case to the control scenario.

2.2 Effectiveness Uncertainty Calculation. A significant challenge of emission-based models such as $PMCAM_x$ is that they depend on accurate estimates of emissions and meteorological inputs. Errors in these inputs impact the model-predicted response to emission changes and hence the effectiveness calculation. We calculate the magnitude and impact of these errors on the ammonia effectiveness and use it to bound our estimates of the ammonia savings potential.

We begin by calculating the average overprediction and underprediction of the model-predicted sulfate concentration, total nitrate (nitric acid gas and nitrate aerosol) concentration, temperature, and relative humidity compared with observations from the Clean Air Status and Trends Network (CASTNet) (*32*, *33*). We estimate the impact of each of these overpredictions or underpredictions by perturbing the $PMCAM_x$ inputs and rerunning the model. For example, the January mean total nitrate overprediction is 40%, hence

TABLE 1. Change in Inorganic $PM_{2.5}$ Concentration Due to a 10% Reduction in Ammonia Emissions for Base Conditions and Accounting for Upper and Lower Bound Biases in $PMCAM_x$ Inputs

month		lower bound	base	upper bound
January	reduction in inorganic $PM_{2.5}$ for 10% NH_3 emission reduction	2.7%	5.7%	8.7%
	% change in effectiveness relative to the base case	−53%		53%
July	reduction in inorganic $PM_{2.5}$ for 10% NH_3 emission reduction	1.0%	1.4%	1.7%
	% change in effectiveness relative to the base case	−28%		24%

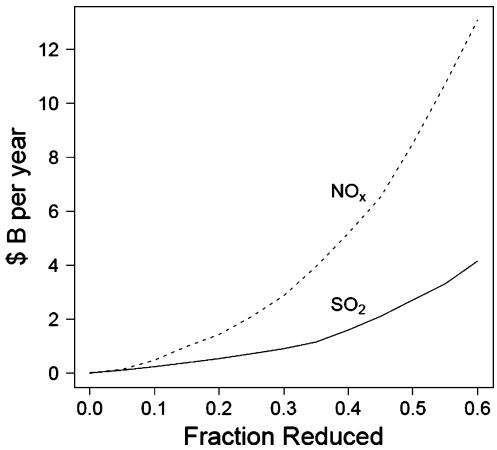

FIGURE 2. Annual cost function for reductions in NO_x (dashed) and SO_2 (solid) as calculated using AirControlNET version 4.0.

we decrease the NO_x emissions by a factor of $0.71 = {}^1/_{1.4}$. We find that an overprediction in nitrate concentration causes an over-estimate of the ammonia effectiveness, because the gas-phase/aerosol-phase partitioning is limited more by the ammonia concentration than the nitrate concentration (compared to the observations). A complete description of these calculations and the effect in the errors in the sulfate, total nitrate, total ammonia, temperature, and relative humidity on the ammonia effectiveness is provided in the Supporting Information.

The upper uncertainty bound is calculated by simultaneously applying perturbations for all of the biased inputs that increase the ammonia effectiveness, and the lower uncertainty bound is similarly calculated with those biases which decrease the ammonia effectiveness. The results of this calculation are shown in Table 1 and are discussed in Section 3.1. The uncertainty bound is estimated by multiplying the ammonia savings potential by the percent difference between the ammonia effectiveness uncertainty bound and the base effectiveness.

2.3 Cost Calculation. The costs for NO_x and SO_2 controls are estimated from AirControlNET version 4.0 (*34*). AirControlNET is a relational database tool which includes a "Least-Cost Module" that selects the set of source controls that achieve a specific emission reduction goal at minimum cost. From the year 2001 data, the domain average cost of emission reduction is calculated for each pollutant as a function of percentage reduced. These are convex functions as shown in Figure 2; each reduction in emissions costs more than the previous reduction. The costs for SO_2 controls are less than the costs for NO_x controls on a percent reduced basis. These annual costs are divided by 12 to yield monthly costs for January and July.

2.4 Ammonia Savings Potential. The ammonia savings potential is the cost of applying SO_2 and NO_x controls in order to achieve the same decrease in ambient inorganic $PM_{2.5}$ concentration as a reduction in ammonia emissions. We begin with the case of no ammonia reductions. We use the results of the cost and effectiveness calculations described above to conduct a least-cost optimization. We select the set of paired SO_2 and NO_x emission reduction scenarios that yield the greatest reduction in $PM_{2.5}$ at each cost increment. The result is a cost-curve relating the costs of NO_x and SO_2 controls to the optimal reduction in $PM_{2.5}$.

If we relax the constraint and allow ammonia emission reductions in the optimization, it is possible to achieve larger reductions in $PM_{2.5}$ at lower cost. We repeat the optimization of SO_2 and NO_x costs (omitting NH_3 control costs) for four different cases corresponding to the 10%, 20%, 30%, and 50% ammonia emission reduction scenarios. For a given level of $PM_{2.5}$ reduction, the ammonia savings potential for an x% reduction in NH_3 emissions is the cost difference between the x% curve and the 0% curve, divided by the tons of NH_3 emissions reduced. We compare the ammonia savings potential with estimated ammonia control costs from technology-based models. Control technologies whose costs are less than the ammonia savings potential represent opportunities to reduce inorganic $PM_{2.5}$ concentrations at a cost lower than the most cost-effective controls on SO_2 and NO_x sources.

3. Results

3.1 NH_3 Controls are More Effective in Winter; SO_2 Controls are More Effective in Summer. The reductions in inorganic $PM_{2.5}$ in response to a 50% emission reduction for NH_3, SO_2, or NO_x are shown in Figure 3. In January, the NH_3 emission reductions are the most effective in reducing inorganic $PM_{2.5}$ concentrations, while in July, reductions in SO_2 emissions yield the largest decrease. In the summer, most of the inorganic aerosol is sulfate (70% at CASTNet locations), and the thermodynamic equilibrium for nitrate favors the gas phase; therefore, SO_2 controls are most effective, and NH_3 controls have little impact. In the winter, $PMCAM_x$ predicts that SO_2 controls will not be especially effective, despite the fact that approximately half of the inorganic $PM_{2.5}$ is composed of sulfate. As the sulfate is reduced, more ammonia becomes available, some of which forms aerosol ammonium nitrate. The sulfate is partially replaced by nitrate, limiting the effectiveness of SO_2 controls. However, winter reductions in NH_3 cause reductions in both ammonium and nitrate $PM_{2.5}$. As the total ammonia is reduced, less is available to form aerosol ammonium nitrate. These results compare favorably with the observation-based Thermodynamic Model with Removal (*20*).

The sensitivity to ammonia is not uniform across the domain. While locations in the Northeast and Midwest regions are similar to the domain average, several locations in the South are more sensitive to NO_x than NH_3 emission reductions in the winter. This may be explained by lower nitrate concentrations at these locations. A more detailed analysis is appropriate for these locations as the ammonia savings potential may deviate from the domain average.

To derive quantitative bounds on the uncertainty, the $PMCAM_x$ inputs are perturbed relative to the difference in the model predictions and the CASTNet observations as described in Section 2.2. As shown in Table 1, in January, the ammonia effectiveness uncertainty bounds are ± 53%, while in July they are −28%/+24%. The uncertainties in January are larger in part because ammonium nitrate concentrations are higher, thus the impact on inorganic $PM_{2.5}$ is larger.

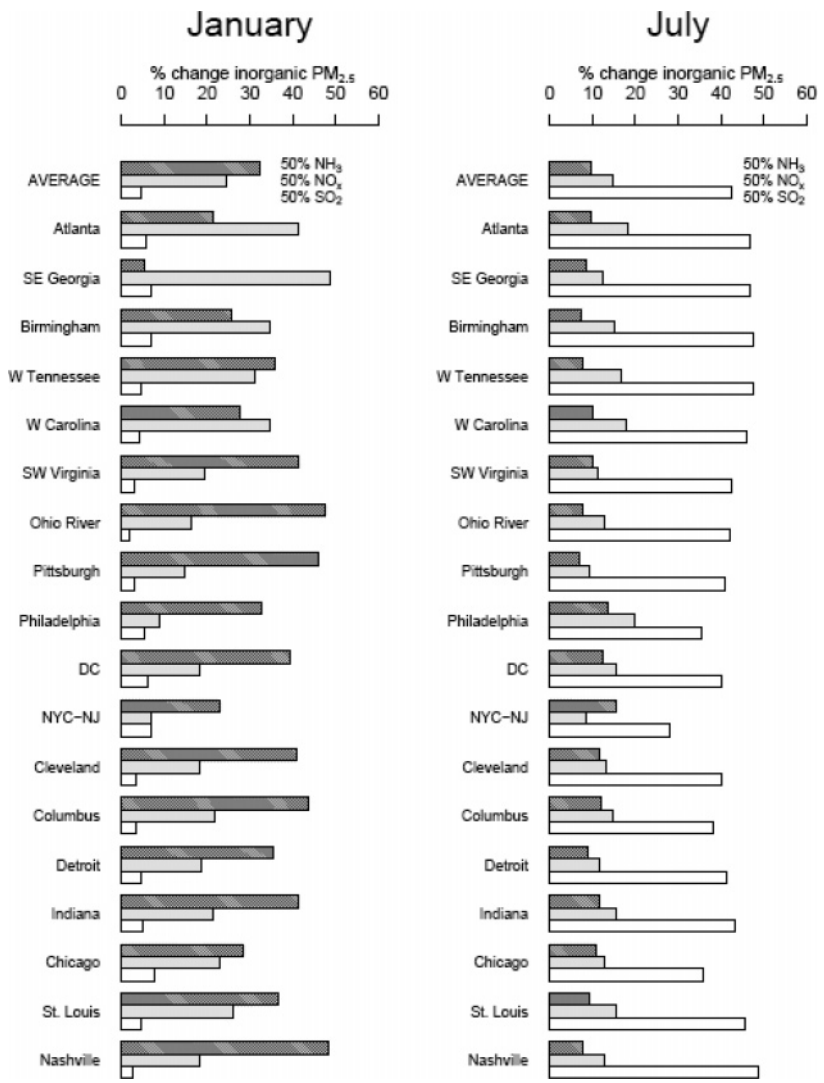

FIGURE 3. Effectiveness measured as the PMCAM$_x$ predicted change in inorganic PM$_{2.5}$ for a domain-wide 50% reduction in precursor emissions: black shading for NH$_3$, gray for NO$_x$, and white for SO$_2$. See Figure 1 for the map of non-attainment grid cells that match these locations.

3.2 Ammonia Savings Potential is Large During Winter. The ammonia savings potential is sizable for the winter test period, but it is considerably smaller during the summer. In Figure 4, each plotted curve is the set of most cost-effective SO_2 and NO_x control strategies for a 0% and 50% NH_3 emission reduction. The shading denotes the fraction of the costs attributable to either NO_x or SO_2 controls. For January, the reduction in ammonia emissions has a large impact on the cost-effectiveness of the SO_2 and NO_x control strategies, as noted by the difference in the scale on the x-axis in Figure 4. Since NO_x and SO_2 emission reductions cause a similar reduction in inorganic $PM_{2.5}$ in January, the most cost-effective strategies are composed of a mix of controls on both SO_2 and NO_x sources. For July, the SO_2 emission reductions are the most effective. NO_x controls are found in the optimized control strategies only after the SO_2 controls have been exhausted. However, NO_x controls are both more expensive and yield less benefit than SO_2 controls; therefore, the slope of the curve increases dramatically. Also in July, the 50% reduction in NH_3 emissions has little impact on cost-effectiveness of the SO_2 and NO_x control strategies.

Figure 5 shows the most cost-effective SO_2 and NO_x control strategies for the 0%, 10%, 20%, 30%, and 50% ammonia emission reduction cases. The ammonia savings potential for an x% decrease in NH_3 emissions is the cost difference (vertical distance in Figure 5) between the 0% NH_3 emission reduction curve and the x% NH_3 emission reduction curve, divided by the tons of NH_3 emissions reduced.

In Figure 6, the ammonia savings potential potential is calculated for a 2 μg m^{-3} reduction in $PM_{2.5}$, which corresponds to a 23% reduction in January and 21% reduction in July for inorganic $PM_{2.5}$ in non-attainment areas. A reduction of 2 μg m^{-3} in the annual average would achieve attainment in 70% of the non-attainment areas in the Eastern United States. Dotted lines denote the uncertainty bounds and are calculated by multiplying the best-estimate by the upper and lower bounds listed in Table 1.

The uncertainty bounds for the ammonia savings potential potential in January range from \$7,800 ton^{-1} to \$28,000 ton^{-1}, with a best estimate of \$18,000 ton^{-1}. In July, the uncertainty bounds range from \$260 ton^{-1} to \$440 ton^{-1}, with a best estimate of \$350 ton^{-1}. While this range is large, the next section demonstrates that there are several NH_3 control strategies that have costs less than the lower-bound ammonia savings potential estimate, and therefore are cost-effective compared to controls on NO_x and SO_2 emission sources.

3.3 Promising Ammonia Control Strategies. Table 2 lists potential control strategies and their average costs (\$ ton^{-1}) as reported by three different ammonia cost models: Air-ControlNET version 4.0 for U.S. emissions, the Regional Air

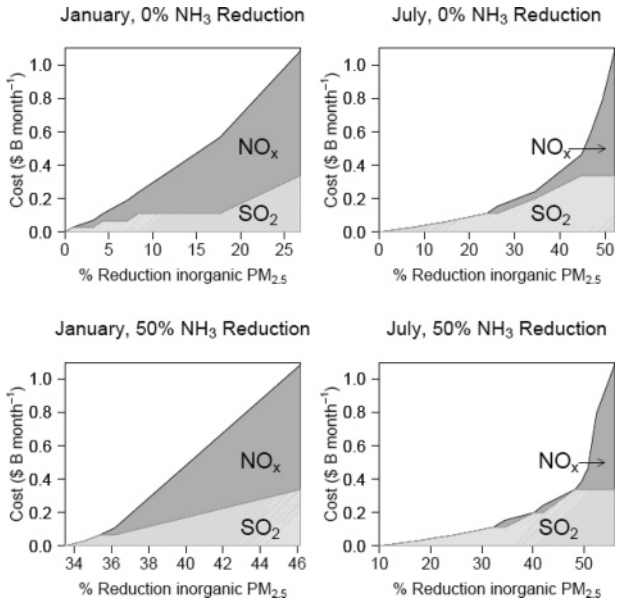

FIGURE 4. Least-cost optimal SO_2 and NO_x emission control costs necessary to achieve a given reduction in ambient inorganic $PM_{2.5}$. The area under the curve is shaded to denote the fraction of the costs from either SO_2 or NO_x controls.

Pollution Information and Simulation (RAINS) model for Europe (*35*, *36*), and the National Ammonia Reduction Strategy Evaluation System (NARSES) model for the United Kingdom (*24*). Costs are converted to 2003 U.S. dollars ($1 = 0.82 [euro] = 0.57 £), future costs are discounted using a 7% interest rate, and the capital lifetimes depend on the control technology. Many of the technologies listed in Table 2 are straightforward techniques that are widely applicable; therefore, it is reasonable to compare the cost estimates from the UK and Europe to U.S. costs despite differences in farming practices.

Several control strategies are available that have costs lower than the winter ammonia savings potential and hence are cost-effective compared to the cost of SO_2 and NO_x emission reductions. In July, few control options are available for less than the lower bound ammonia savings potential.

4. Discussion

Reductions in ammonia emissions have been excluded from regulatory planning owing to uncertainty in the level of emissions and feasibility of control strategies. Recent advances in ammonia emission inventories have provided more reliable estimates of emissions. In this study, we have bounded the uncertainty such that it is possible to quantify the cost-effectiveness of ammonia emission controls, and we find that reductions in ammonia emissions are cost-effective when compared with controls on SO_2 and NO_x, especially in the winter.

In the coming fifteen years, federal emission regulations will go into effect that will substantially decrease emissions of SO_2 and NO_x. These emission reductions will likely cause most locations in the Eastern United States to move into attainment for the $PM_{2.5}$ annual standard of 15 μg m^{-3} (*37*). For many locations that require additional controls to achieve their air quality goals, this analysis shows that ammonia emission reductions are more cost-effective than further reductions in NO_x and SO_2. For locations which are expected

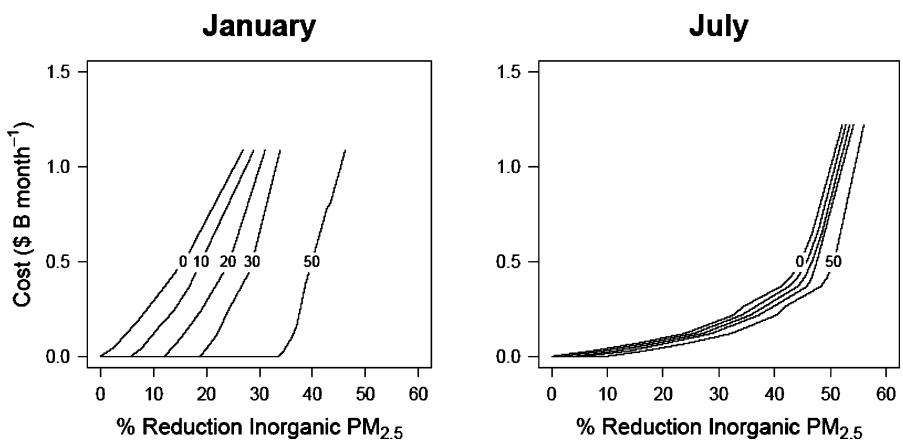

FIGURE 5. Least-cost optimal NO_x and SO_2 reductions for each NH_3 emission reduction interval for January and July. From left to right the curves represent a 0%, 10%, 20%, 30%, and 50% reduction in NH_3 emissions. The ammonia savings potential potential for an *x*% NH_3 emission reduction scenario is defined as the cost difference (vertical distance) between the 0% curve and the *x*% NH_3 reduction scenario curve.

TABLE 2. Costs of NH_3 Control Technologies

technology	$ ton^{-1}	source
chemical additives to swine housing floor	70	AirControlNET
chemical additives to cattle housing floor	200	AirControlNET
cover broiler manure	30−300	NARSES, RAINS
replace urea fertilizer with ammonium nitrate	500	NARSES, RAINS
allow crust formation on lagoon surface	700	NARSES
immediate incorporation of applied manure	800	NARSES
chemical additives to poultry housing floor	900	AirControlNet
adapt poultry housing	2,500	RAINS
apply manure with trailing shoe	7,500	NARSES
adapt dairy housing	10,000	RAINS
rigid cover for pig manure stores	15,000	NARSES
belt drying layer (chicken) manure	20,000	NARSES

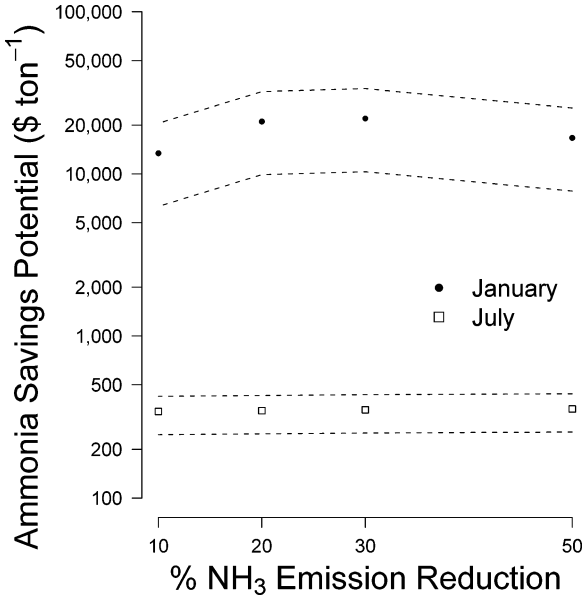

FIGURE 6. Ammonia savings potential on a per ton basis for January (filled circles) and July (open squares) for a 2 μg m^{-3} reduction in inorganic $PM_{2.5}$ at non-attainment areas in the Eastern United States. Dotted lines denote uncertainty bounds.

to be near the standard, ammonia emission reductions are a low-cost opportunity to hedge against the uncertainty of future growth projections.

In addition to inorganic $PM_{2.5}$ reductions, ammonia emission controls have significant environmental benefits to ecosystem acidification and nutrient loading. An often held misperception in the air quality community is that ammonia neutralizes the acidifying impacts of sulfuric acid and nitric acid deposition. In the atmosphere, ammonia is a basic compound, but it undergoes transformations in the ecosystem that have a net acidifying impact (*38*−*40*). Nitrifying soil bacteria convert ammonium to nitrate. Plants preferentially uptake NH_3 rather than NH_4^+ from the soil, which causes the H^+ ion to accumulate. Ammonia is also a nutrient source to microbiological and plant communities. Deposition to coastal ecosystems leads to changes in the species composition, eutrophication, and degradation of estuaries and fishing grounds (*41*).

However, there are significant policy challenges to regulating ammonia emissions. Enforcement and monitoring are complex as the emissions from farms are from buildings, storage facilities, and fertilized fields rather than a single point. Care must be taken to ensure that atmospheric ammonia emission reductions do not simply shift the discharge of nitrogenous pollutants to other media. Agricultural operations contribute to the degradation of ground and surface waters by nitrate runoff and nutrient loading. Farms also contribute to climate change by emissions of the greenhouse gas N_2O (*42*).

The most promising control strategies are those that improve the overall nitrogen efficiency of the agricultural operation. Nitrogen emitted to the environment from the farm must be replaced by purchasing feed or fertilizers; therefore, improved nitrogen efficiency can be both an environmental and economic benefit. Potential examples include optimized feed rations, low-emission fertilizers, and more accurate nitrogen accounting to avoid excessive feeding or fertilizer application. Livestock and crops often receive nitrogen in excess; therefore, reductions in nitrogen inputs to the farm are feasible with little or no reduction in yield (*43*, *44*). These require little structural change in the farming operation and can be used seasonally when benefits for control of inorganic $PM_{2.5}$ are largest.

During the winter in urban areas, vehicles equipped with catalytic converters are a significant source of ammonia (*45*). Little is known about the costs of controlling these sources; further research in this area is a high priority.

While there are definite challenges inherent in the policy options, ammonia emission reductions offer significant cost savings compared to further controls on SO_2 and NO_x. With innovative regulatory strategies, these cost savings can be realized.

Acknowledgments

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Supporting Information Available

Model bias and uncertainty calculations, tables of bias in model predictions and $PMCAM_x$ model domain, figure of $PMCAM_x$ model domain; $PMCAM_x$ air quality model evaluation, and figures of comparisons of Jefferson Street and Birmingham monitoring locations' data. This material is available free of charge via the Internet at http://pubs.acs.org.

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