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Estimating Model-Based Marginal Societal Health Benefits of Air Pollution Emission Reductions in the United States and Canada

Hakami et al.

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Estimating Model-Based Marginal Societal Health Benefits of Air Pollution Emission Reductions in the United States and Canada

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with a Commentary by the HEI Review Committee

Research Report 218
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ABOUT HEI

The Health Effects Institute is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the effects of air pollution on health. To accomplish its mission, the Institute

- identifies the highest-priority areas for health effects research
- competitively funds and oversees research projects
- provides an intensive independent review of HEI-supported studies and related research
- integrates HEI's research results with those of other institutions into broader evaluations
- communicates the results of HEI's research and analyses to public and private decision-makers.

HEI typically receives balanced funding from the US Environmental Protection Agency and the worldwide motor vehicle industry. Frequently, other public and private organizations in the United States and around the world also support major projects or research programs. HEI has funded more than 380 research projects in North America, Europe, Asia, and Latin America, the results of which have informed decisions regarding carbon monoxide, air toxics, nitrogen oxides, diesel exhaust, ozone, particulate matter, and other pollutants. These results have appeared in more than 260 comprehensive reports published by HEI, as well as in more than 2,500 articles in the peer-reviewed literature.

HEI's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization. The Research Committee solicits input from HEI sponsors and other stakeholders and works with scientific staff to develop a Five-Year Strategic Plan, select research projects for funding, and oversee their conduct. The HEI Improved Exposure Assessment Studies Review Panel, which has no role in selecting or overseeing studies, works with staff to evaluate and interpret the results of funded studies and related research.

All project results and accompanying comments by the Review Panel are widely disseminated through HEI's website (*www.healtheffects.org*), reports, newsletters, annual conferences, and presentations to legislative bodies and public agencies.

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Research Report 218, *Estimating Model-Based Marginal Societal Health Benefits of Air Pollution Emission Reductions in the United States and Canada*, A. Hakami et al.

INTRODUCTION

Particulate matter (PM*) is an air pollutant that is a mixture of organic (e.g., carbon-containing) and inorganic microscopic particles and liquid droplets suspended in the air. Anthropogenic PM can be emitted directly from point (e.g., smokestacks) and mobile (e.g., vehicle exhaust) sources, in which case it is referred to as a primary PM emission. PM can also form by atmospheric gas-to-particle conversion of pollutants such as ammonia (NH_3), nitrogen oxides (NO_x), and sulfur dioxide (SO_2), and is referred to as a secondary PM. Due to its ubiquity and links to human health, PM is commonly used as a proxy for overall air quality (World Health Organization [WHO] 2022).

Size determines how far a particle can reach the respiratory tract and influences what health effects can result from exposure. Fine particles (PM ≤2.5 µm in aerodynamic diameter, or $PM_{2.5}$) and chemical compounds attached to the particle surface can deposit deep within the lungs and directly enter the bloodstream (Li et al. 2022). Even at relatively low exposure levels, PM is associated with a myriad of adverse health effects — including respiratory and cardiovascular diseases — and is recognized as a leading risk factor for morbidity and mortality worldwide (GBD 2020; IARC 2016; US EPA 2019). The substantial body of evidence has led the United States Environmental Protection Agency (US EPA) to conclude that the link between exposure to $PM_{2.5}$ and mortality is causal (US EPA 2019).

Beyond explicit health effects, air pollution has numerous social and economic costs to society, including increased healthcare expenditures and reduced productivity resulting from air pollution-induced chronic diseases, disability, and death (Alexeeff et al. 2022; Pandey et al. 2021; US EPA 2011). Air pollution also can decrease road and scenic visibility and decrease agricultural yields (US EPA 2011). Furthermore, carbon dioxide (CO_2), a potential driver of global climate change, is frequently co-emitted with anthropogenic air pollutants (Orru et al. 2017). Accordingly, research suggests that air pollution reductions can have a multitude of benefits to society, even in regions with air pollution levels below current regulatory standards (Meng et al. 2021; Schraufnagel et al. 2019; Tschofen et al. 2019; US EPA 2011). However, research evaluating the costs and benefits of air pollution emissions reductions has been limited by computational challenges associated with accurate modeling and characterization of uncertainty. Thus, prior studies often applied unrealistic assumptions and simplifications.

To estimate the monetary health benefits associated with reducing emissions from transportation and other selected sources, Dr. Amir Hakami of Carleton University submitted an application to HEI titled "Quantifying marginal societal health benefits of transportation emission reductions in the United States and Canada" in response to HEI's Request for Applications RFA 17-2, Health Effects of Air Pollution. This RFA provided a mechanism for investigators whose area of interest broadly centered on novel and important aspects of the health effects of air pollutants, particularly those derived from motor vehicle emissions. Dr. Hakami and colleagues proposed to apply a novel extension to the US EPA's Community Multiscale Air Quality model (CMAQ) that they had developed to improve the way health benefits were estimated and then create a database of these benefits for specific locations and emissions sources in the United States and Canada. The health benefits estimates would be based on a method of monetizing premature mortality from long-term $PM_{2.5}$ exposure. They also proposed to estimate the climate change cobenefit of reduced emissions by quantifying the reduction in co-emitted CO_2. HEI funded the study because it would improve upon a state-of-the-art air quality model and apply the most recent emissions inventories to estimate the benefit of cutting emissions for different geographic locations, while also addressing many modeling concerns with sensitivity analyses. The study also offered an approach that fits well under the broader umbrella of HEI's accountability research program, which evaluates the effectiveness of air pollution reduction policies aimed at improving air quality and public health.

This Commentary provides the HEI Review Committee's independent evaluation of the study. It is intended to aid the sponsors of HEI and the public by highlighting both the strengths and limitations of the study and by placing the Investigators' Report into scientific and regulatory perspective.

Dr. Amir Hakami's 3-year study, "Quantifying Marginal Societal Health Benefits of Transportation Emission Reductions in the United States and Canada," began in October 2018. Total expenditures were $399,417. The draft Investigators' Report from Hakami and colleagues was received for review in October 2022. A revised report, received in April 2023, was accepted for publication in June 2023. During the review process, the HEI Review Committee and the investigators had the opportunity to exchange comments and clarify issues in both the Investigators' Report and the Review Committee's Commentary.

* A list of abbreviations and other terms appears at the end of this volume.

SCIENTIFIC AND REGULATORY BACKGROUND

REGULATING AIR POLLUTION IN THE UNITED STATES AND CANADA

Air pollution in the United States is regulated by the Clean Air Act, which sets allowable concentrations, known as National Ambient Air Quality Standards (NAAQS), for major pollutants including PM, NO_x, and SO_2. To attain the NAAQS, federal- and state-level policies are adopted to control air pollutant emissions from large stationary sources like power plants or mobile sources like cars and trucks by mandating fuel changes, requiring installation of control technologies, or capping total or facility-specific emission rates. In Canada, air quality policy is broadly directed by the Canadian Environmental Protection Act of 1999. A multistakeholder council recommends nonlegally binding Canadian Ambient Air Quality Standards (CAAQS), which are voluntarily adopted by states and territories. Air quality is actively managed to achieve the CAAQS by individual air zones (Canadian Council of Ministers of the Environment [CCME]) 2021).

Although air pollution levels have declined in high-income countries over the past few decades, health impacts continue to be seen at levels at and below current air quality standards (Brauer et al. 2019, 2022; Brunekreef et al. 2021; Chen and Hoek 2020; Dominici et al. 2019, 2022). Accordingly, the WHO revised its air quality guidelines (WHO 2021), and some governmental agencies, such as the US EPA, have lowered the regulatory standard for $PM_{2.5}$ (US EPA 2024b). These agencies continue to review the scientific evidence to evaluate the need for even lower standards. Alternatively, future regulations could focus on specific sources of emissions or particular components or fractions of PM to optimize health benefits (Henneman et al. 2023; Kwon et al. 2020; McDuffie et al. 2021).

EVALUATING THE COSTS AND BENEFITS OF AIR POLLUTION REGULATIONS

The US EPA is mandated to evaluate the costs and benefits of the Clean Air Act and any regulation considered to be economically significant or innovative. To date, the US EPA has released one retrospective (US EPA 1997) and two prospective (US EPA 1999, 2011) studies of the benefits of the Clean Air Act relative to its costs. The US EPA has also released regulatory impact analyses (RIAs) that estimate the expected costs and benefits of numerous individual rules and their alternatives proposed under the Clean Air Act. RIAs generally compare expected future scenarios with and without regulation (or different versions of the regulation) to assess whether the proposed rules are likely to be cost effective and meet their stated goals. They consider such factors as implementation and compliance costs and the projected changes in air quality, health outcomes, and nonmonetary effects.

The US EPA uses estimates of avoided mortality, hospital admissions, and other outcomes — and economic assumptions about the value of those avoided outcomes — to characterize the monetary benefits of improved health from the regulation or intervention. The monetary benefits are calculated using a metric called benefits-per-ton (BPT, see Sidebar). As an illustration, the US EPA's recently completed RIA estimated the net benefit of lowering the $PM_{2.5}$ NAAQS from 12 to the current standard of 9 $\mu g/m^3$ in 2032 to be $22 billion (US EPA 2024a). In response to climate change concerns, the US EPA may also examine the additional benefits of decreased CO_2 emissions that result from proposed controls on other pollutants that are emitted simultaneously (US EPA 2022). Canada also conducts similar analyses (Health Canada 2022).

BPT estimation has historically been conducted in a two-step process by first linking health benefits with changes in ambient air pollutant concentrations using such tools as the US EPA's Environmental Benefits Mapping and Analysis Program (BenMAP) or Health Canada's Air Quality Benefits Assessment Tool (AQBAT) and then linking the outputs to emissions grouped by source or location using separate air quality modeling (Judek et al. 2012; US EPA 2023). Although some advances in modeling approaches have been developed in recent years, they often rely on unrealistic modeling assumptions and simplifications such as ignoring secondary PM formation. Hakami and colleagues integrated BPT estimation by directly linking the health benefits to a wide array of individual source- and location-specific pollutant emissions using an adjoint extension of CMAQ (CMAQ-ADJ). The CMAQ model is among the most widely used computer models for simulating the quantity, chemical, and physical transformation, and the geographical transport of numerous pollutants in the atmosphere over time (US EPA 2012).

To what extent have regulations achieved their intended goals in reducing emissions, air pollution concentrations, and adverse health impacts? These are questions that accountability research attempts to answer. Over the past two decades, HEI has emerged as a leader in air pollution accountability research, contributing to research design, funding, and study oversight. In 2003, an HEI working group developed a conceptual framework for conducting air pollution accountability research and outlined methods and opportunities for future research (HEI Accountability Working Group 2003). See the Preface for more details about HEI's involvement in accountability research. Through a series of RFAs over the past two decades, HEI has now funded 23 studies that have assessed a wide variety of regulations targeting both point and mobile sources of air pollution, the indirect effects of the COVID-19 lockdowns on air quality, and the development of methods to assist in environmental justice policy. The study by Hakami and colleagues uniquely contributes to the accountability research program by analyzing economic factors and estimating BPTs using current data to shape future policy. Additionally, it examines past emissions data to estimate the observed benefit of the Clean Air Act over a 15-year period.

Estimating Societal Benefits

Hakami and colleagues evaluated the health benefits of reduced emissions using the **BPT** metric, which combines economic valuation, epidemiology, and pollutant information. In this study, the BPT metric specifically estimated the annual monetary cost of a reduced mortality risk from long-term $PM_{2.5}$ exposure in dollars for every 1 ton of emissions reduction (see equation).

$$BPT\left(\frac{\$}{1\ ton\ emissions}\right) = VSL\left(\frac{\$}{death}\right) \times CRF\left(\frac{deaths}{\Delta PM_{2.5}}\right) \times \frac{\Delta PM_{2.5}}{\Delta source\ emissions}$$

The monetary cost of a reduced mortality risk is known as the **value of a statistical life (VSL)** and is the first term on the right-hand side of the equation. Importantly, VSL is not the value placed on a person's life nor does it represent the loss in economic productivity associated with a premature death. VSL is a theoretical concept that measures the collective societal demand to forgo the consumption of goods and services to reduce associated health risks and is used by governments for cost-benefit analyses (Colmer 2020). For example, a policy might be expected to reduce the risk of death by 0.001%, or 1 averted death per 100,000 people. If people are willing to pay $10 on average for that risk reduction, then collectively, society would incur a cost of $1 million to save one statistical life.

The second term in the BPT equation, **concentration–response function (CRF)**, is the estimated association between $PM_{2.5}$ exposure and death derived from published epidemiological studies. The final term in the equation represents the relationship between the source emissions and the ultimate time- and location-specific $PM_{2.5}$ exposure reductions (Δ denotes the difference in $PM_{2.5}$ concentrations or source emissions over the study period) and is estimated by the adjoint CMAQ simulations.

SUMMARY OF APPROACH AND METHODS

STUDY AIMS AND APPROACH

To estimate the societal benefits associated with reducing emissions from transportation and other select sources, Dr. Hakami and colleagues aimed to accomplish the following:

- Estimate location-specific BPTs associated with certain emissions sectors throughout the United States and Canada and create a publicly available database of the location-specific BPTs.
- Evaluate the robustness of the BPT estimates using sensitivity analyses of
    - the spatial resolution of the adjoint model simulations
    - the effect of estimating annual BPT estimates based on selected representative time periods
    - the emissions levels in the United States as affected by past and future controls
    - the choice and form of the epidemiological CRFs.
- Estimate the cobenefits of reduced combustion-based CO_2 emitted from transportation sources and other select sectors.

Hakami and colleagues sought to create a BPT database that could be used by decision-makers to develop air pollution control policies that would result in the greatest health benefits to society. To achieve this goal, they further developed a novel extension to CMAQ. CMAQ-ADJ enabled the investigators to estimate BPTs by seamlessly linking data from recent large-scale epidemiological studies back to the original pollutant emissions in backward simulations. CMAQ-ADJ also allowed for detailed sensitivity analyses to assess the robustness of the results. BPTs of reduced 2016 emissions of NH_3 and criteria pollutants $PM_{2.5}$, NO_x, and SO_2 were calculated.

METHODS AND STUDY DESIGN

Hakami and colleagues developed the CMAQ-ADJ and have extensively validated and applied the model (Hakami et al. 2007; Zhao et al. 2020). CMAQ-ADJ accounts for complex atmospheric processes, including advection and diffusion in horizontal and vertical space; gas-phase chemistry; cloud processes; aerosol formation, growth, aging, and thermodynamics; and dry and wet deposition. Detailed information on pollutant emissions data came from the 2016 Emissions Inventory Platform, beta version (National Emissions Inventory Collaborative 2019) and the MOtor Vehicle Emission Simulation–version 3 (MOVES3) (US EPA 2021), which contains detailed inventories for emissions from point, nonpoint, and on-road sources. Model simulations were conducted for the contiguous United States and most of Canada (inclusive of ≥ 97.3% of the Canadian population) using 2016 meteorology, and they accounted for cross-border effects. The analysis included daily 2016 emissions of primary $PM_{2.5}$, NO_x, SO_2, and NH_3, and covered emissions from both ground-level and elevated sources.

Hakami and colleagues applied 2016 inflation-adjusted VSLs published by the Government of Canada and the US EPA of $7.5 million CAD and $10.2 million USD, respectively (Chestnut and De Civita 2009; US EPA 2010), with other recommended time-lag adjustments. Population data were linked at the census-tract level. The CRF selected for the primary analyses was derived from the Global Exposure Mortality Model (GEMM) because it incorporated 41 cohorts from 16 countries and a range of $PM_{2.5}$ exposures, and it could be applied to both the United States and Canada (Burnett et al. 2018). The BPTs along with the level of emissions were used to estimate the total burden of each pollutant. Because of their location specificity, adjoint-based BPTs do not have strong sectoral signatures, so BPTs were reported for different source elevations with no designation to any specific sector.

Because reducing combustion-related pollutant emissions can simultaneously reduce CO_2 emissions, the authors also estimated the cobenefit-per-ton of CO_2 using the relative emissions profiles of copollutants for each sector. Unlike the BPTs, cobenefits exhibit strong sectoral differences and were evaluated by 60 different sectors and vehicle or engine types (e.g., on-road, off-road, gasoline, diesel, passenger, industrial, construction, goods movement, agricultural, lawn and garden, and recreation). Because targeted replacement of certain gasoline or diesel vehicles with electric vehicles would require evaluation of local electricity production, the authors also evaluated cobenefits associated with natural gas and coal electricity-generating units.

Sensitivity Analyses of the Adjoint CMAQ Model

Spatial resolution and representative time periods The CMAQ-ADJ model is computationally demanding, even on powerful supercomputers, necessitating a trade-off between the length of the simulated time period and the spatial resolution. The investigators first simulated the annual BPTs at 36-km resolution using hourly emissions for the contiguous United States and most of Canada. To allow for a finer spatial scale, they then selected representative time periods. Two-week periods were simulated for each season at 12-km resolution, and thus annual estimates were derived from eight representative weeks. The periods were selected separately for the United States and Canada (**Commentary Figure 1**) by using bias functions to identify the two-week periods most representative of the seasonal average and most consistent with the 36-km modeling. To evaluate any differences at an even finer spatial scale, Hakami and colleagues simulated summertime BPTs for Los Angeles, California, and New York City, New York, using hourly emissions within the selected 2-week episode at 4-km and 1-km resolutions.

CRF selection The selected CRF is a key component of BPT calculations by providing information on estimated mortality for a given change in $PM_{2.5}$ exposure (see Sidebar). To evaluate how the selected CRF would affect BPT estimates, Hakami and colleagues compared the primary-selected CRF reported by the GEMM (Burnett et al. 2018) in the United States to four alternative CRFs reported by high-quality epidemiological studies with large cohorts — two from the American Cancer Society Cancer Prevention Study II (Krewski et al. 2009; Turner et al. 2016), one from the National Health Interview Survey (NHIS) (Pope et al. 2019), and one from a recent meta-analysis (Chen and Hoek 2020). Although the studies used the same cohort, Krewski and colleagues (2009) was included because it is widely used in health impact assessments, and Turner and colleagues (2016) was included because it applied improved methods for CRF estimation. For the United States, Hakami and colleagues calculated the mean BPTs from all five CRFs and estimated the variation.

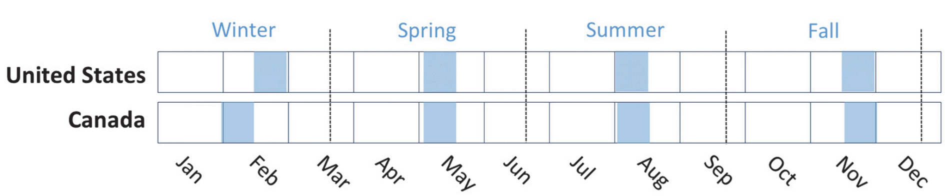
Emissions levels The primary analysis applied 2016 emissions data, which was the most recent data available at the time. To evaluate changes in the BPT estimates by large-scale changes in emissions, Hakami and colleagues also simulated the selected summer and winter time periods using available emissions data from 2001 and emissions projections for 2028. The selected years were chosen because that is when the national emissions inventories were available.

The authors conducted these sensitivity analyses and qualitatively rated the level of uncertainty from spatial resolution, time period selection, CRFs, and emissions levels as low, medium, and high. They also compared the BPT estimates to those of three other reduced complexity models (Muller 2014; Heo et al. 2016a,b; Tessum et al. 2017).

SUMMARY OF KEY FINDINGS

BENEFITS OF EMISSIONS REDUCTIONS

BPT estimates for the United States and Canada are mapped in **Commentary Figures 2** and **3**, respectively; note that BPT scales differ by pollutant and show cross-border effects. The BPTs represent the societal benefit of reducing emissions at a specific location and as such do not provide exact information on where the health benefits will be realized. For both countries, BPTs were largest for primary $PM_{2.5}$, followed by NH_3. SO_2 and NO_x were much smaller. BPTs were generally higher in the eastern half of the United States, with the highest levels near large cities, particularly in the northeast and California. However, BPTs were more uniform across the United States for SO_2 except for California where BPTs were highest. Note also that BPTs can be lower than expected in high pollution areas because the impact from incremental increases in emissions would be trivial, whereas BPTs can be



Commentary Figure 1. Two-week season- and country-specific time periods in 2016 selected for CMAQ-ADJ model simulation at 12-km resolution.

elevated in low emission and uninhabited areas due to secondary $PM_{2.5}$ formation that can affect health elsewhere. Due to the complex atmospheric chemistry of PM precursors, BPTs can also be negative in exceptional circumstances where secondary PM formation dominates. The authors reported that BPTs for primary $PM_{2.5}$ were relatively stable across seasons, whereas variability was observed across seasons for precursor emissions due to the influences of temperature and humidity.

Considering BPTs and cumulative domestic emissions, Hakami and colleagues estimated that the total burden of all primary $PM_{2.5}$ emissions was estimated at $585B USD and $60B CAD for the United States and Canada, respectively (**Commentary Table**). Including cross-border transport of pollution, the national burden in the United States and Canada increases to $608B USD and $71B CAD, respectively. Furthermore, primary $PM_{2.5}$ accounted for about 70% of the total burden of long-term exposure to $PM_{2.5}$ from all emissions evaluated (i.e., primary $PM_{2.5}$, NH_3, NO_x, and SO_2) in both countries. Taking advantage of the unequal distribution of BPTs across each country and using a graphing method called a Lorenz curve (see Investigators' Report Figure 8) to identify disparities in BPTs over the full range of emissions levels, the authors reported that just 10% of primary $PM_{2.5}$ emissions associated with the highest BPTs were responsible for 35% and 60% of the primary $PM_{2.5}$ attributed health burden in the United States and Canada, respectively. The total burden of domestic NH_3 emissions was estimated to be $129B USD in the United States and $11B CAD in Canada ($137B USD and $16B CAD when including cross-border transport of pollution) and accounted for about 16% of the total burden of long-term exposure to $PM_{2.5}$ in each country. 10% of NH_3 emissions could be attributed to about half of the NH_3-attributed health burden in both countries.

Commentary Table. Total Burden and Disparity of Domestic Emissions Contributing to Long-term $PM_{2.5}$ Exposure

	United States		Canada	
	Total Burden (Billion USD)	%Burden of 10% of Emissions	Total Burden (Billion CAD)	%Burden of 10% of Emissions
Primary $PM_{2.5}$	$585	35%	$60	60%
NH_3	$129	50%	$11	50%
NO_x	$43	35%	$3	37%
SO_2	$48	20%	$2	30%
Total	**$805**		**$77**	

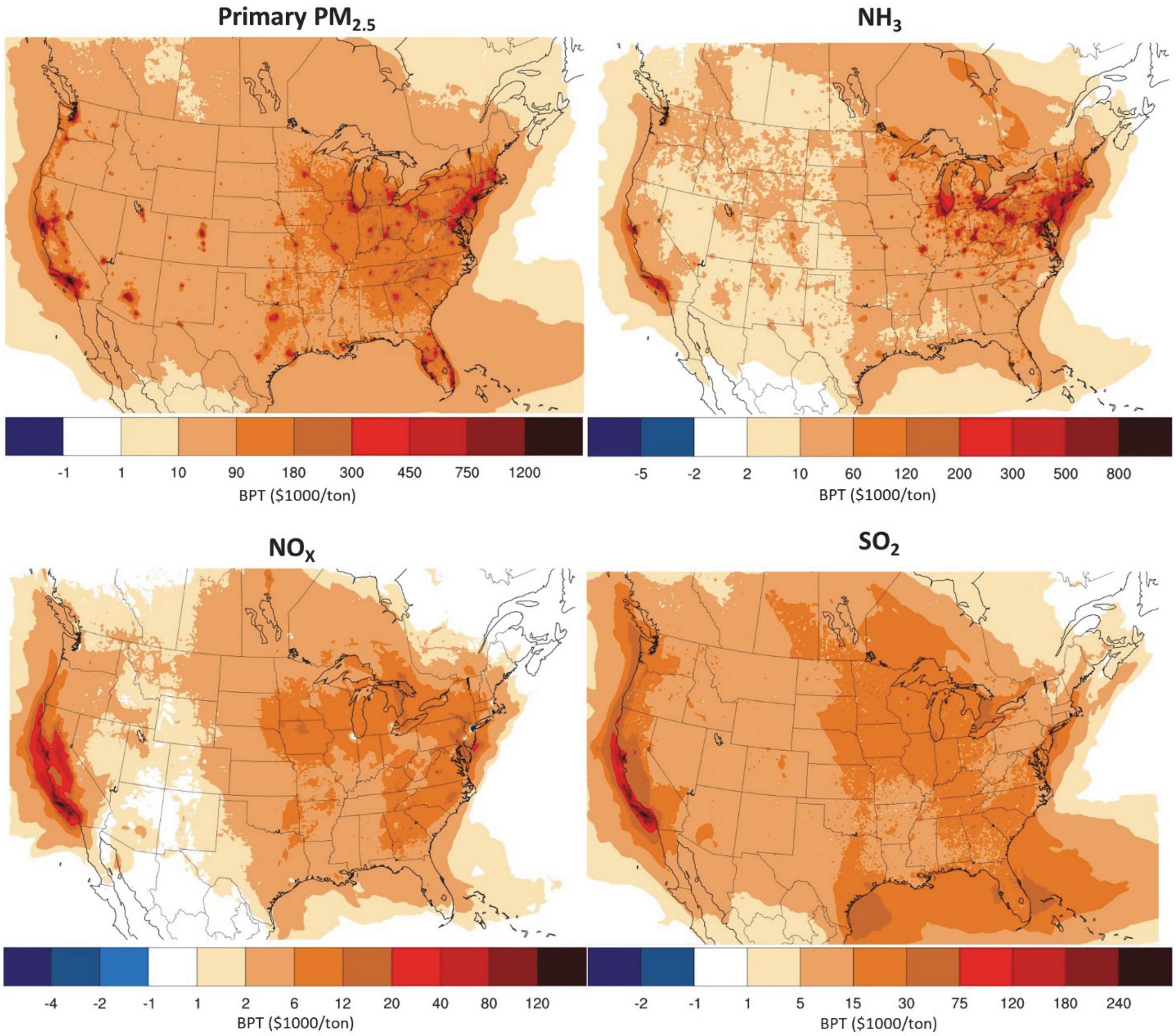
BPT SENSITIVITY TO DIFFERENT MODEL INPUTS

Choosing different seasonal time periods minimally affected BPTs. Agreement between annual BPTs estimated from daily 36-km resolution and 2-week seasonal time periods at 12-km resolution was high for primary $PM_{2.5}$. Specifically, the coefficients of determination (R^2) were high (0.98 and 0.99 for the United States and Canada, respectively) and measures of bias and random error were low. Agreement between the daily and 2-week time period estimated BPTs was slightly lower for precursor emissions. For example, in the United States, R^2 ranged between 0.86 for SO_2 and up to 0.94 for NO_x, and measures of random error were slightly higher than for primary $PM_{2.5}$. The authors rated the uncertainty in time period selection as low.

The spatial resolution of the CMAQ modeling affected BPTs. When comparing BPTs estimated at 36-, 12-, 4-, and 1-km resolution in Los Angeles and New York City, investigators found good agreement (moderate to high R^2) and a tendency toward higher BPTs at finer resolutions, particularly for precursor emissions. Dependence on model resolution was more pronounced in Los Angeles. The authors rated the uncertainty in spatial resolution as medium.

Choice of CRF also affected BPTs. Averaged across the United States, GEMM BPTs were most similar to BPTs derived from the American Cancer Society cohort ACS-16 (Turner et al. 2016) CRF, followed by the Chen and Hoek (2020) CRF, although there were some regional differences. GEMM BPTs were slightly higher than BPTs derived from CRFs of the American Cancer Society cohort ACS-09 (Krewski et al. 2009) and NHIS (Pope et al. 2019), but lower than the BPTs derived from the Chen and Hoek (2020) CRF. The authors reported that relative comparisons of BPTs varied by individual location based on the CRF shape and location-specific pollutant concentrations. Mean BPTs across all five CRFs and the coefficient of variation (COV) are reported in **Commentary Figure 4**. The COV was generally lower in areas with higher BPTs, such as much of the eastern United States, and ranged from 15% to 50% for different pollutants. The authors rated the uncertainty in CRF selection as medium-high.

Temporal changes in emissions from 2001, 2016, and 2028 projections led to some variation in BPTs estimates. The authors reported that the variation was due to nonlinearities in the GEMM CRF, which mostly affected primary $PM_{2.5}$ and SO_2, and atmospheric processes, which mostly affected precursors NH_3 and NO_x. BPTs were more consistent for the years 2016 and 2028 compared with 2001, which the authors interpreted to mean that BPTs would be more robust to future scenarios. They rated the uncertainty due to temporal changes in emissions as medium but stated that the uncertainty was likely to decrease in the future.

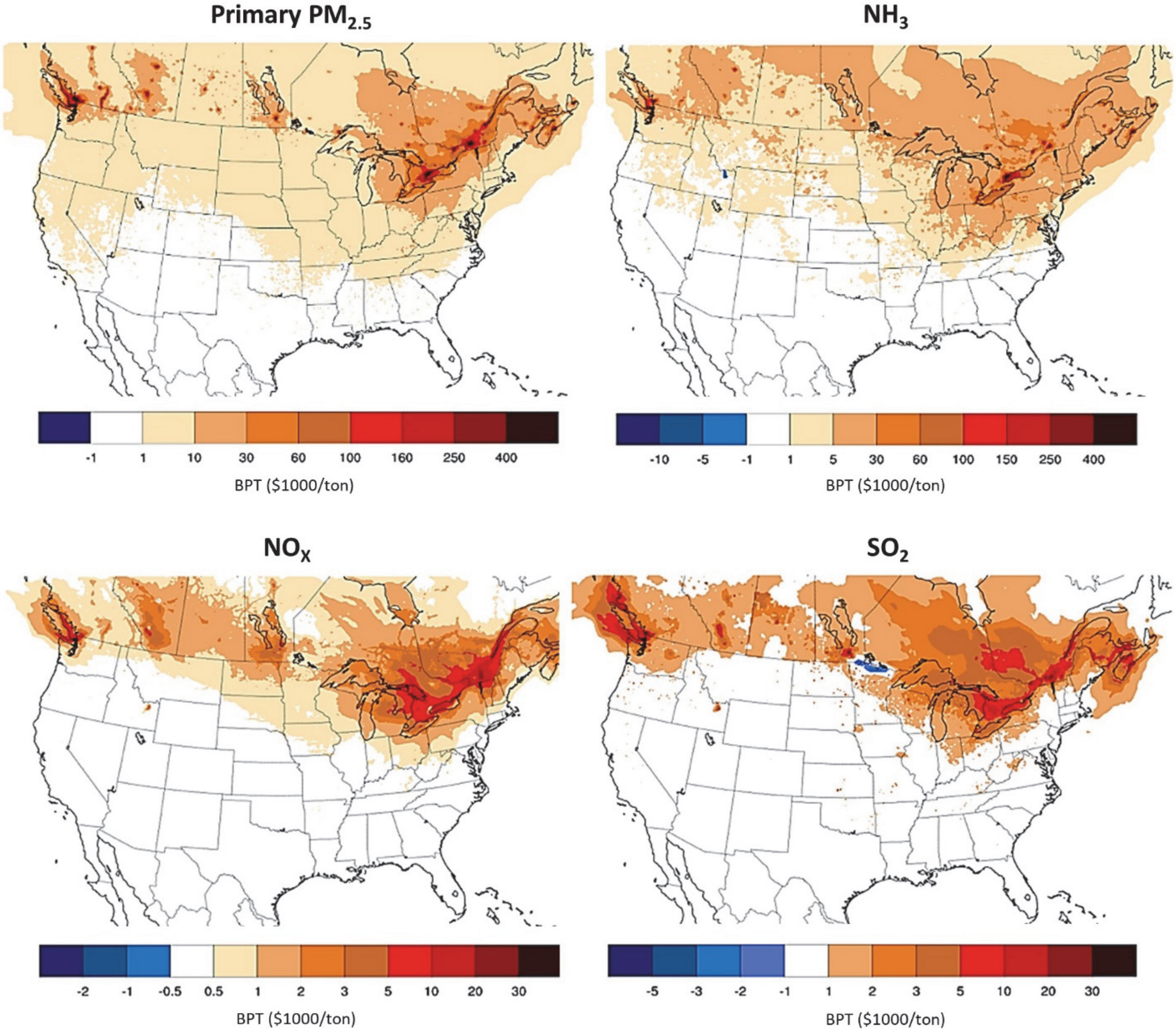


Commentary Figure 2. US 2016 surface BPTs by emitted pollutant. Note that BPT scales differ by pollutant.

Compared with BPTs derived from the previously published reduced complexity models, the CMAQ-ADJ BPT estimates were in good agreement for primary $PM_{2.5}$ (R^2 0.738–0.816), low-moderate agreement for NH_3 (R^2 0.358–0.664), and low agreement for NO_x and SO_2 (R^2 0–0.342) emissions.

CLIMATE COBENEFITS OF EMISSIONS REDUCTIONS

Cobenefits varied widely across different sectors as shown for selected vehicle and engine types in **Commentary Figure 5**. These cobenefits represent the estimated health benefits of reduced $PM_{2.5}$ exposure following a reduction in combustion-related CO_2 emissions. Generally, cobenefits were higher for diesel vehicles and engines compared with gasoline ones, and highest for off-road vehicles and engines, particularly those with 2-stroke engines. Evaluation by vintage within a specific vehicle sector revealed substantial cobenefit differences, with older vehicles showing higher cobenefits. For example, in Los Angeles, the cobenefit for diesel transit buses made in 2002 was 15 times higher than for buses made in 2016. Compared with the 2016 buses, the buses made in 2002 produced more than three times the total burden, even though their annual mileage was lower and only a third of them were still on the road. Such information would be useful for policymakers and planners in developing targeted climate action plans. National cobenefit maps and city-specific cobenefit data for other sectors are available in the Investigators' Report Appendix B (available on the *HEI website*). In terms of electricity generation, the cobenefits were higher for coal-powered compared with natural gas-powered electricity. The complete results for BPTs and cobenefits are available at *https://doi.org/10.5683/SP3/DTS44O*.

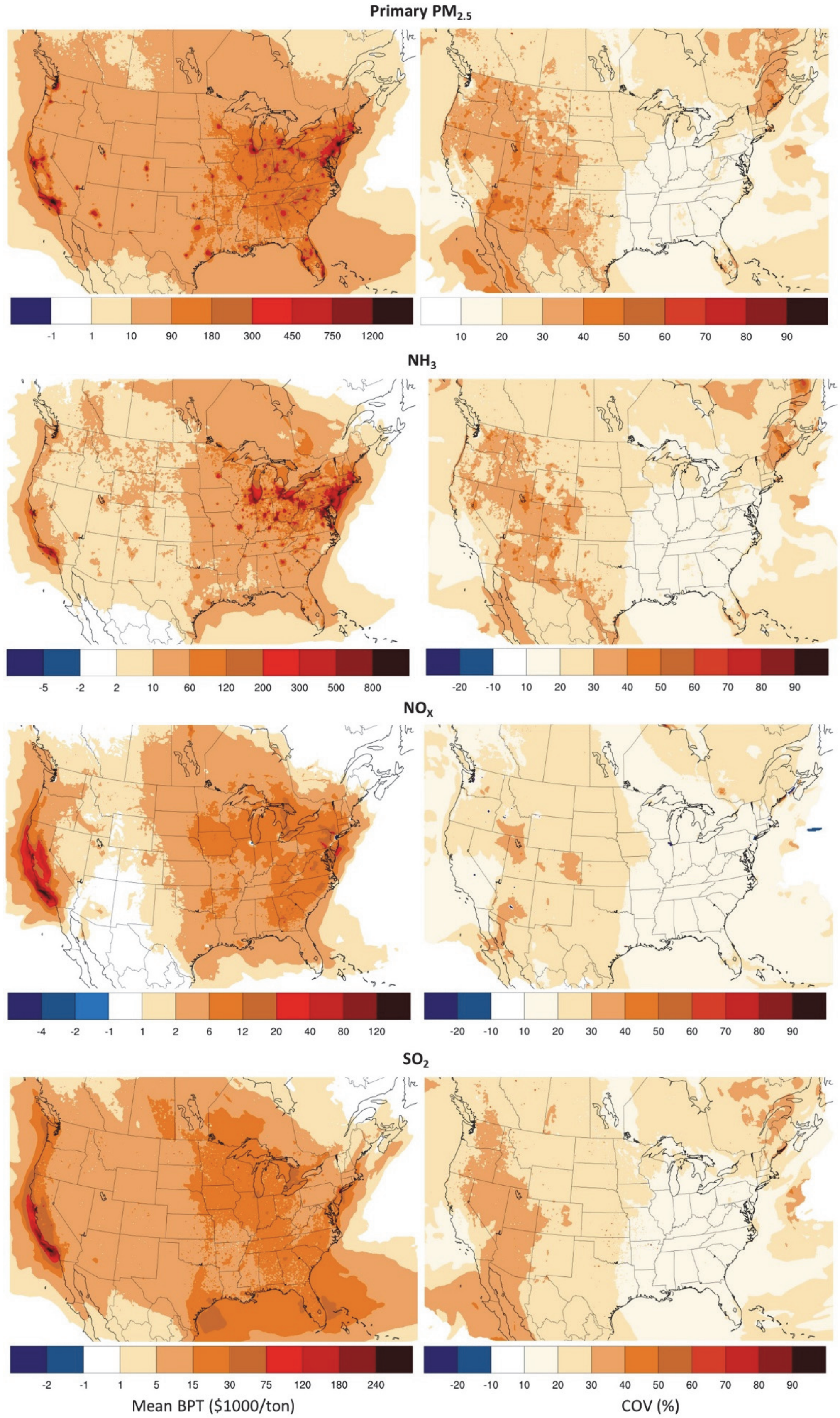


Commentary Figure 3. Canada 2016 surface BPTs by emitted pollutant. Note that BPT scales differ by pollutant.

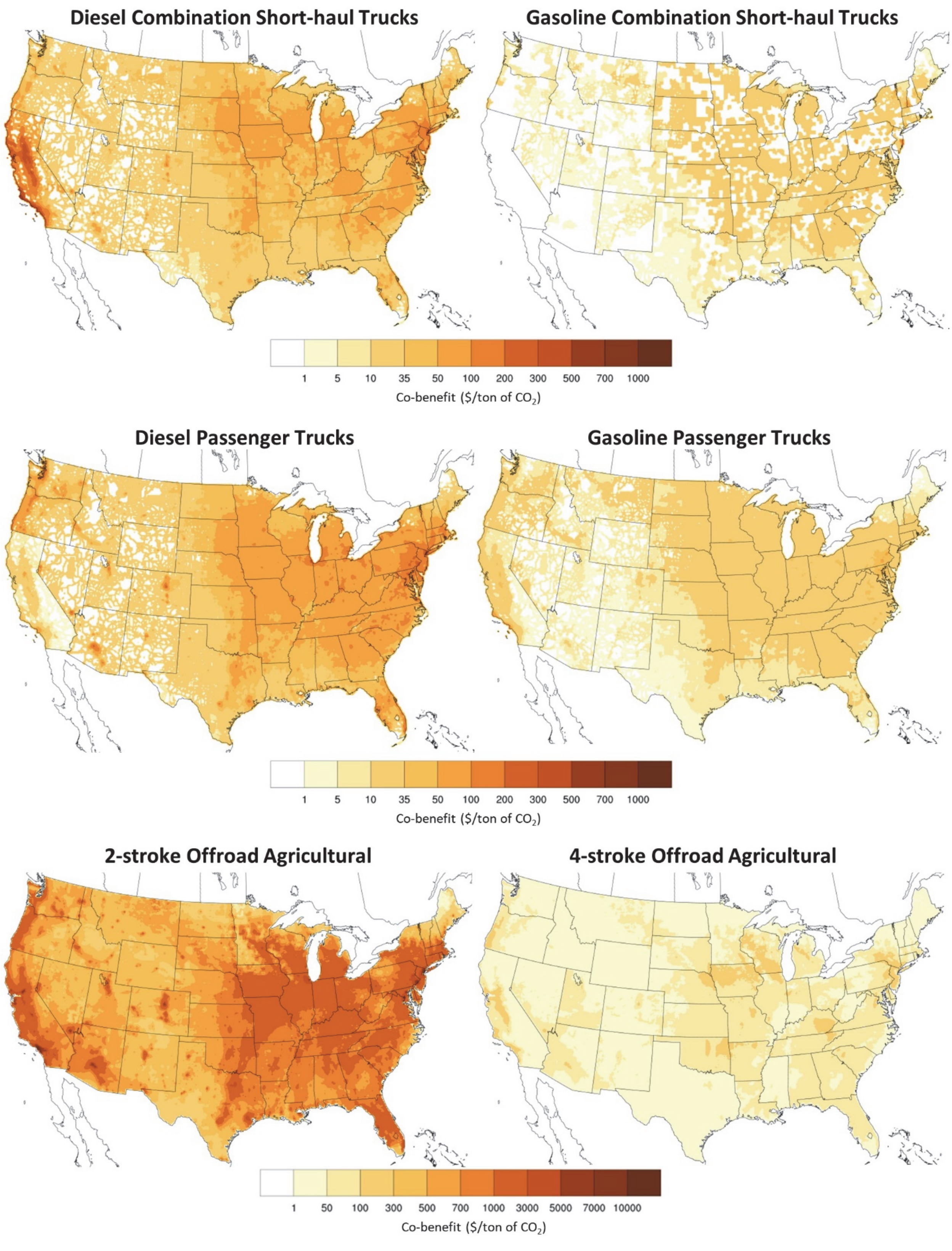
EVALUATION BY THE HEI REVIEW COMMITTEE

This health impact study evaluated the benefits of decreased air pollutant emissions from different classes of vehicles and major point sources that contribute to ambient $PM_{2.5}$ exposure across the United States and Canada. Hakami and colleagues simulated the effect of multipollutant emissions at 12-km resolution using a novel adjoint extension of the US EPA's CMAQ model. This state-of-the-art model enabled them to create a database of source- and location-specific BPTs of reduced emissions. They also estimated the climate-change relevant cobenefit of the concomitant reduction in CO_2 associated with the same emissions sources. BPTs were largest for primary $PM_{2.5}$, followed by NH_3, and lowest for SO_2 and NO_x. BPTs were generally higher in the eastern half of the United States, with the highest levels near large cities, particularly in the northeast and California. The total burden of primary $PM_{2.5}$ was estimated at $585B USD and $60B CAD for the United States and Canada, respectively, and accounted for about 70% of the total burden of long-term exposure to $PM_{2.5}$ from all domestic emissions sources. The results suggested that a relatively small percentage of emissions accounted for most of the health burden.

In its independent review of the study, the HEI Review Committee thought that the report was methodologically rigorous, thorough, and policy-relevant and agreed that the authors' interpretations and conclusions were supported by the results. They considered a key strength of the study to be the use of a high spatial resolution adjoint air quality model to evaluate the effect of location-specific sources of air pollutants and the benefits of mitigating those sources, including cross-border effects between the United States and Canada.



Commentary Figure 4. Mean and COV US 2016 surface BPTs from primary $PM_{2.5}$ emissions combined over five CRFs at 12-km resolution. Note that BPT and COV scales differ by pollutant.



Commentary Figure 5. Cobenefits of selected vehicle sectors. Note that cobenefit scales differ by sector.

Indicating the areas and sectors with the highest emissions reduction benefits can support targeted and efficient air quality and decarbonization policies that reduce the emissions of relevant air pollutants. The Committee appreciated that Hakami and colleagues evaluated the CO_2 cobenefits for a multitude of policy-relevant transportation sectors, including various on- and off-road vehicles using gasoline- or diesel-powered engines and vehicles of different classes such as passenger, public transit buses, and construction, among others. These examples were considered representative of the sectors that are expected to change over the next 10 years as newer energy technologies increase market share, older vehicle fleets are replaced, and electrification makes greater inroads. In its evaluation, the Review Committee also identified some limitations and areas warranting further research as described below.

MODEL UNCERTAINTY

A weakness of health impact studies is that the models rely on numerous assumptions and uncertainties that can affect the results. Some assumptions, however, are required to make the analyses feasible in terms of computing resources. The Committee appreciated Hakami's efforts to conduct a comprehensive and thoughtful sensitivity analysis to evaluate the model assumptions and how that would change the BPT estimates. The investigators evaluated the effect of the shape of the CRF extracted from relevant published epidemiological studies; changes between past, current, and projected future emissions; the spatial resolution of the model; and the selection of time-period episodes for simulations.

Incorporation of different CRFs substantially influenced the estimated BPTs, and the authors considered this to be the largest source of uncertainty in the study. The CRF used for the primary analysis was a sublinear curve reported using the GEMM (Burnett et al. 2018) and was compared to a supralinear curve reported using a US nationally representative cohort (Pope et al. 2019), linear curves derived from the American Cancer Society — Cancer Prevention Studies-II cohort (Krewski et al. 2009; Turner et al. 2016), and a linear curve derived from a 107-study meta-analysis (Chen and Hoek 2020). BPTs estimated using the GEMM were similar to those estimated using Turner and colleagues (2016) and Chen and Hoek (2020) but were generally larger than BPTs estimated using Krewski and colleagues (2009) and Pope and colleagues (2019).

In general, the uncertainty in the BPT estimates due to the CRF was inversely proportional to the magnitude of the estimated BPTs across locations. For example, in the Midwest and East Coast regions of the United States, where the BPT estimates were generally higher, there was lower variation in estimated BPTs between the different input exposure–response functions. Hakami and colleagues explained that the differences in estimated BPTs by CRF were driven by changes in the hazard ratios across different $PM_{2.5}$ exposure concentrations, which were most dramatic for the sublinear and supralinear curves. The Committee noted that this explanation was reasonable but thought that the report could have been improved by further discussion of the differences. They noted that this sensitivity analysis illustrated the importance of CRF selection in health impact studies and the need for high-quality, population-representative epidemiological studies with relevant exposure ranges.

In contrast to the exposure–response function inputs, the BPT estimates were less sensitive to changes in the spatial resolution of the adjoint CMAQ model. Hakami and colleagues compared BPTs estimated from models with spatial resolutions of 1, 4, 12, and 36 km. Due to computational constraints, models with the 1- and 4-km resolution were evaluated only for two large metropolitan areas, Los Angeles and New York City. They found that in general, higher-resolution models estimated higher BPTs but that the results remained relatively consistent across the different spatial resolutions. The Committee noted that the results were not as sensitive to spatial resolution as one might expect and agreed with Hakami's conclusion that the coarser 12-km resolution used for the primary analysis was appropriate at a national level. Finally, the Committee appreciated the reported comparisons with other BPT estimates, which demonstrated consistency with less complex modeling methods.

OPPORTUNITIES FOR FUTURE RESEARCH

This study focused on emissions that contributed to chronic $PM_{2.5}$ exposure, including primary $PM_{2.5}$, NO_x, SO_2, and NH_3. Consequently, the study did not evaluate the direct and indirect effects of other air pollutants, likely leading to an underestimation of the health benefits reported. In particular, the Committee noted that NO_x can affect human health directly and through its contribution to ground-level ozone formation (Badida et al. 2023; Boogaard et al. 2023; Dominici et al. 2022; Yang et al. 2023). Ambient ozone is also an important greenhouse gas that is relevant to climate change, and its formation exhibits substantial spatial and temporal heterogeneity. Thus, location-specific benefit estimates of reduced ozone have the potential to inform air pollution and climate policy on both the national and local scale and should be investigated in future studies. It is also worth noting that the benefits in this study were evaluated based only on chronic exposure in relation to premature mortality. Although premature mortality accounts for 98% of the benefits associated with chronic $PM_{2.5}$ health effects (US EPA 2024a), it will also be useful for future health impact studies to consider acute exposures and other important health and economic indicators such as chronic diseases, disability, and lost workdays.

SUMMARY AND CONCLUSIONS

In summary, this health impact study evaluated the BPTs of decreased 2001, 2016, and projected 2028 air pollutant emissions from different sources that contribute to mortality from chronic ambient $PM_{2.5}$ exposure across the United States and Canada. Hakami and colleagues used a novel adjoint extension of the CMAQ model at high spatial resolution to produce a database of source- and location-specific BPTs. Their results suggest that reductions in a relatively small proportion of emissions could yield a large societal health benefit. In addition, focused emissions reductions in certain transportation sectors, including off-road engines and heavy-duty diesel vehicles, could yield climate and health cobenefits. The Committee noted that the study included rigorous sensitivity analyses to assess the uncertainties of BPT estimates and that the emissions sectors evaluated were policy-relevant. They recommended that future studies evaluate the effect of additional pollutants, such as NO_x and ozone, that have both health and climate importance.

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ABBREVIATIONS AND OTHER ITEMS

ACS-09	CRF from Krewski et al. 2009
ACS-CPS-II	American Cancer Society–Cancer Prevention Studies-II
APEEP	Air Pollution Emission Experiments and Policy Analysis
AP2	successor to APEEP
AQBAT	Air Quality Benefits Assessment Tool
BenMAP	Environmental Benefits Mapping and Analysis Program
BPT	benefit-per-ton
CAAQS	Canadian Ambient Air Quality Standards
CanCHEC	Canadian Census Health and Environment Cohort
CCME	Canadian Council of Ministers of the Environment
CHEN	CRF from Chen and Hoek 2020
CMAQ	Community Multiscale Air Quality
CMAQ-ADJ	CMAQ-adjoint version
CO_2	carbon dioxide
COV	coefficient of variation
CRF	concentration–response function
CTM	chemical transport model
EASIUR	Estimating Air Pollution Social Impact Using Regression
GEMM	global exposure mortality model
GHG	greenhouse gas
H-CMAQ	hemispheric CMAQ
HR	hazard ratio
InMAP	Intervention Model for Air Pollution
MB	marginal benefit
MOVES3	MOtor Vehicle Emission Simulation–version 3
NAAQS	National Ambient Air Quality Standards
NEIC	National Emission Inventory Collaborative
NH_3	ammonia
NHIS	National Health Interview Survey
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
PM	particulate matter
$PM_{2.5}$	particulate matter 2.5 µm in aerodynamic diameter
RIA	regulatory impact analysis
R^2	coefficient of determination
SO_2	sulfur dioxide
US EPA	United States Environmental Protection Agency
VMT	vehicle miles traveled
VSL	value of a statistical life
WHO	World Health Organization
WRF	weather research and forecast model

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