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LETTER

Climate, air quality, and health benefits of a carbon fee-and-rebate bill in Massachusetts, USA

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Abstract

State and regional climate policies in the United States are becoming more prevalent. Quantifying these policies' health co-benefits provides a local and near-term rationale for actions that also mitigate global climate change and its accompanying harms. Here, we assess the health benefits of a carbon fee-and-rebate policy directed at fuel use in transport, residential and commercial buildings and industry in Massachusetts. We find that the air pollution reductions from this policy would save 340 lives (95% CI: 82–590), 64% of which would occur in Massachusetts, and reduce carbon emissions by 33 million metric tons, with 2017 as an implementation year, through 2040. When monetized, the benefits to health may be larger than the benefits from climate mitigation, but are sensitive to valuation methods, discount rates, and the leakage rate of natural gas, among other factors. These benefits derive largely from lower transportation emissions, including volatile organic compounds from gasoline combustion. Reductions in oil and coal use have relatively large benefits, despite their limited use in Massachusetts. This study finds substantial health benefits of a proposed statewide carbon policy in Massachusetts that carries near-term and direct benefit to residents of the commonwealth and demonstrates the importance of co-benefits modeling.

Introduction

The transportation and building sectors contribute heavily to greenhouse gas emissions that drive climate change, and to other harmful air pollutants. In 2015, the transportation sector emitted 1700 million metric tons of CO_2–32% of total US CO_2 emissions. Residential and commercial buildings emitted 570 million metric tons of CO_2–10% of total US CO_2 emissions (US Environmental Protection Agency 2017). Road transportation is the largest contributor to air pollution-related mortality in the US (Caiazzo et al 2013), followed by electric power generation and commercial/residential buildings. Residential combustion alone has been associated with 10 000 deaths per year in the US (Penn et al 2017). Policies that mitigate climate change by reducing fossil fuel consumption can also have health benefits, often termed 'health co-benefits', by improving air quality (Wilkinson et al 2009, Nemet et al 2010, Perry et al 2014, Plachinski et al 2014, Mittal et al 2015, Thompson et al 2016, Haines 2017, Li et al 2018).

Research on co-benefits of carbon policies has found that health benefits can be substantial. The magnitude depends on sectors affected, policy design, and the geographical relationship between source locations and populations exposed to air pollution. In the electrical sector, health co-benefits are greatest for policies that principally displace coal (Siler-Evans et al 2012, Driscoll et al 2015, Buonocore et al 2015, 2016a, 2016b, Li et al 2018). Other studies have modeled hypothetical nation, state, or province-level carbon policies and found that policies targeting multiple economic sectors can have higher co-benefits than policies targeting just one sector, and that health benefits are generally higher if high-emission sources
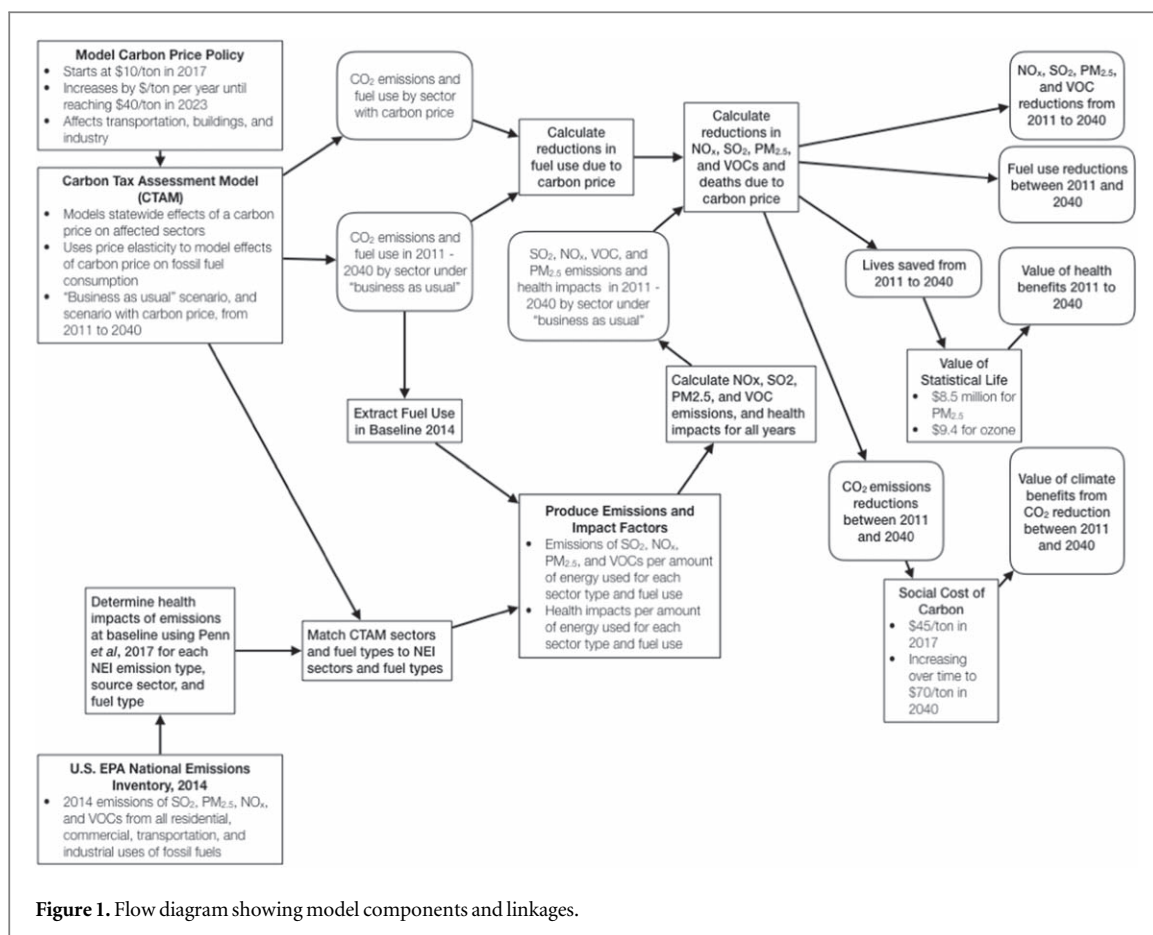
Figure 1. Flow diagram showing model components and linkages.

are reduced (Saari *et al* 2014, Thompson *et al* 2016, Li *et al* 2018). While these studies provide insight into drivers of benefits, they do not examine the benefits of specific state-level policies. This may become increasingly relevant, since with the proposed US withdrawal from the Paris Agreement, 11 states and 271 cities and counties have committed to actions that will meet or exceed greenhouse gas targets required to meet the Paris goals (Sanderson and Knutti 2016, Hepburn 2017, Tollefson 2017, we Are Still In n.d.).

Here, we assess the climate and health benefits of a model carbon fee-and-rebate bill applied to fossil fuel consumption in the transportation, residential, commercial, and industrial sectors in Massachusetts. The fee schedule starts at \$10/ton in 2017, and increases by \$5 yr^{-1}, until it reaches a plateau price of \$40 per ton in 2023, a price similar to many other carbon prices worldwide (Benson n.d., Barrett n.d., The World Bank n.d.). These bills, and our study, exclude electrical generation, since the electrical grid in Massachusetts is covered by the Regional Greenhouse Gas Initiative. We assess benefits from 2017 through 2040, assuming that the carbon price was implemented in 2017. We quantify the health co-benefits in economic terms and compare with monetized climate benefits.

Methods

We developed a model framework that links the following components (figure 1):

- CO_2 emissions and fuel use reductions for Massachusetts from the Carbon Tax Assessment Model (CTAM).

- Emissions of SO_2, NO_x, $PM_{2.5}$, and VOCs for relevant sectors within Massachusetts.

- A Community Multi-Scale Air Quality Model Direct Decoupled Method (CMAQ-DDM)-based impact-per-ton methodology providing state-resolution health benefits per ton of emissions reduced.

Using this framework, we estimated the reductions in fossil fuel use, CO_2 emissions reductions, the reductions in emissions of NO_x, SO_2, $PM_{2.5}$, and VOCs and the consequent health benefits, comparing a 'business-as-usual' (BAU) scenario with a policy scenario, put in monetary terms using standard valuation methodologies.

Modeling the reductions in fuel use and CO_2 emissions

To estimate reductions in fossil fuel use and CO_2 emissions, we used output from CTAM (Nystrom and Zaidi 2013, Breslow *et al* 2014). CTAM is an economic

model that uses price elasticities, differing by fuel type and sector, along with state-specific economic data, including GDP growth, number of households, and existing policies, to estimate how fuel use will change, sector-wide, in response to changes in the price of the fuel. This model relies on future energy use forecasts from the National Energy Modeling System from the US Energy Information Administration, and existing literature on price elasticities of energy.

The carbon emissions from each fuel type and sector are calculated using standard emissions factors. The carbon fee is then applied to these carbon emissions under a BAU scenario, and the expected reduction in fuel consumption in response to the increase in price is calculated using the price elasticity—how fuel consumption changes in response to the change in price. From this fuel use reduction, we calculate the emissions reductions and health benefits of those reductions. To estimate the monetary value of the reductions in CO_2 emissions, we use the social cost of carbon (SCC), a metric for measuring benefits of reducing carebon emissions, and put them in monetary, net-present-value terms. The specific values used here change over time to account for the increase in the marginal impact per ton of carbon emitted in future years, due to nonlinear response of the climate system to increased emissions. They start at \$45 per ton (2017 USD) in 2017, and end at \$70 per ton (2017 USD) in 2040 (Interagency Working Group on Social Cost of Carbon 2016). We present the benefits of CO_2 reductions undiscounted and discounted at 3% yr^{-1}, to be consistent with the discount rate of future impacts internal to each year's estimate of the SCC of an emission in that year.

Estimating reductions in emissions of non-GHG air pollutants, and health benefits

To estimate the reductions in $PM_{2.5}$, SO_2, NO_x, and VOCs from the carbon fee-and-rebate policy, we used emissions data from the US EPA National Emissions Inventory (NEI) from 2014 as our BAU emissions. We used these emissions data along with the BAU fuel consumption from CTAM to create sector-and-fuel type-wide emissions factors for fuel use within Massachusetts. We then used these emissions factors to calculate BAU emissions in future years. The matching between CTAM and NEI fuel types and sectors are described in detail in the supplemental (table S1 is available online at stacks.iop.org/ERL/13/114014/mmedia). To estimate the health benefits of the emissions reductions, in terms of mortality avoided, we used a CMAQ-based impact-per-ton methodology that gives source state-resolution estimates of mortality avoided per ton of pollutant reduced, across multiple source sectors (Levy *et al* 2016, Penn *et al* 2017). CMAQ is a complex atmospheric chemistry, fate, and transport model that is often used by the US EPA to simulate the air quality impacts of air pollution and

energy policies, and is commonly used for research purposes (Buonocore *et al* 2014, Stackelberg *et al* 2013, Roy *et al* 2007, Foley *et al* 2010, US Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division 2012, Fann *et al* 2011, Appel *et al* 2017, Arunachalam *et al* 2011, Byun and Schere 2006).

This impact-per-ton methodology is based on a series of runs with the CMAQ-DDM (Levy *et al* 2016, Penn *et al* 2017). DDM allows for the influence of given emissions sources and pollutants across the modeling domain to be tracked within a given simulation (Napelenok *et al* 2006, Wagstrom *et al* 2008, Itahashi *et al* 2012). The impact-per-ton methodology used here was developed using CMAQ-DDM to individually model the sensitivities of ambient concentrations of $PM_{2.5}$ and ozone to emissions of SO_2, NO_x, $PM_{2.5}$, and VOCs in both winter and summer for multiple sectors within each source state in the US (Cohan *et al* 2005, Bergin *et al* 2012, Itahashi *et al* 2012, Levy *et al* 2016, Penn *et al* 2017). These sensitivities, providing estimates of the air quality impact per ton emitted for each precursor pollutant, were then used to model the health impacts using a concentration-response function of a 1% increase in all-cause mortality per 1 $\mu g\,m^{-3}$ increase in annual average ambient $PM_{2.5}$ levels (95% CI: 0.2–1.8) and a 0.4% increase in daily mortality per 10 ppb increase in ozone concentrations (95% CI: 0.14–0.66), population data from the US Census, and baseline mortality data from the Centers for Disease Control and Prevention. These concentration-response functions were similar to those used in previous studies (Roman *et al* 2008, Driscoll *et al* 2015, Levy *et al* 2016, Buonocore *et al* 2016a, Penn *et al* 2017, Centers for Disease Control and Prevention n.d., Bell 2004, Bell *et al* 2005, Schwartz 2005), and the 95% confidence intervals encompass the variability in concentration-response functions from major epidemiological studies of air pollution (Bell 2004, Bell *et al* 2005, Schwartz 2005, Lepeule *et al* 2012, Driscoll *et al* 2015, Levy *et al* 2016, Penn *et al* 2017). For transportation-related sources, we applied the average of the summer and winter sensitivities; for building-related sources, we used the sensitivities for winter, which assumes that most of the fuel use in these sectors is for heating (US Energy Information Administration 2018).

To put a monetary value on the lives saved from the emissions reductions, we used the value of statistical life (VSL) (Dockins *et al* 2004). This is a willingness-to-pay methodology commonly used in regulatory impact analysis and other policy research applications that captures most of the value of the health benefits from emissions reductions (Dockins *et al* 2004, US Environmental Protection Agency Office of Air Quality Planning and Standards 2011, Siler-evans *et al* 2012, Thompson and Selin 2012, Siler-Evans *et al* 2013, Thompson *et al* 2014, US Environmental Protection Agency, Office of Air and
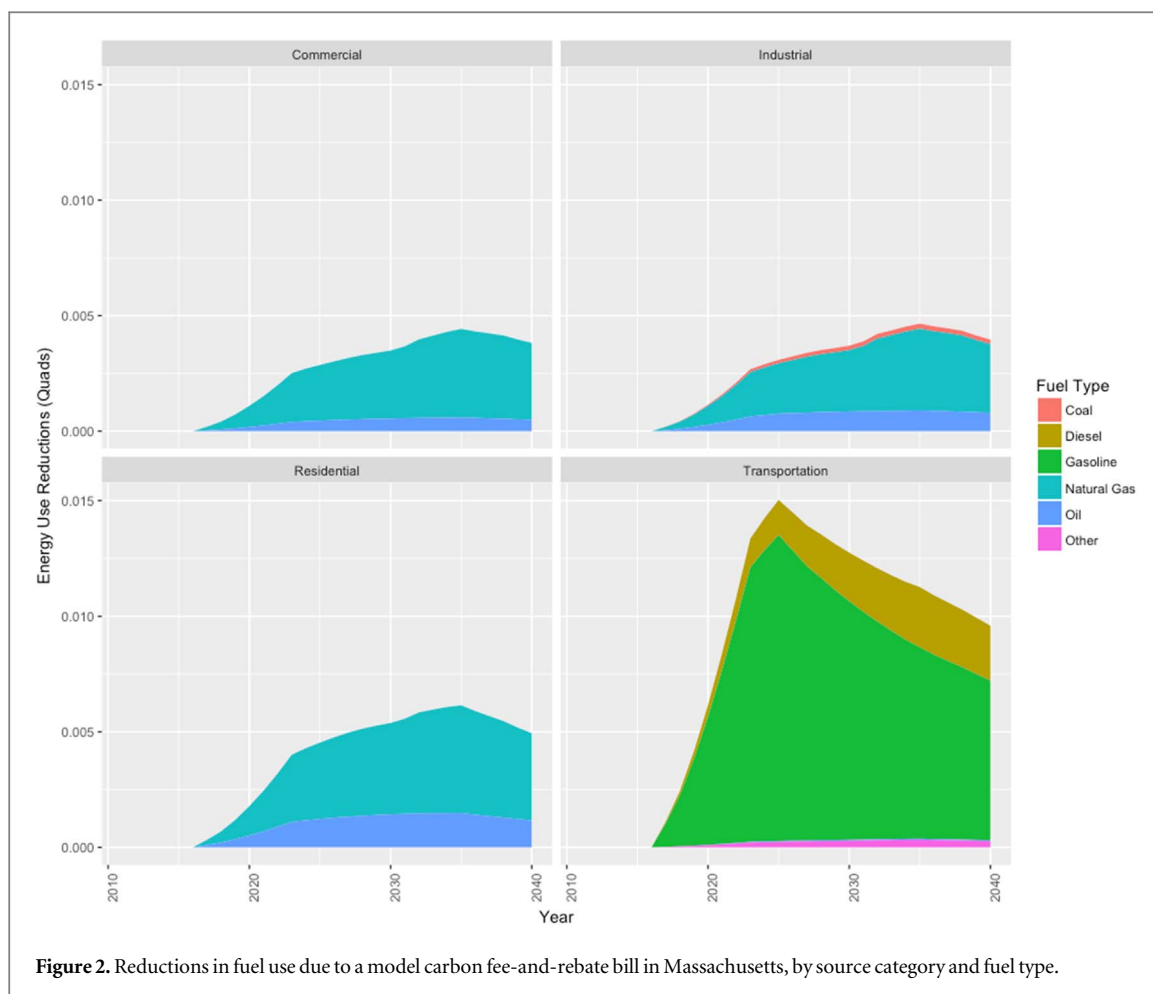
Figure 2. Reductions in fuel use due to a model carbon fee-and-rebate bill in Massachusetts, by source category and fuel type.

Radiation, Office of Air Quality Planning and Standards 2015, Thompson *et al* 2016, Buonocore *et al* 2016a). To account for the delay between $PM_{2.5}$ exposure and mortality, we use a standard cessation lag (US Environmental Protection Agency Office of Air Quality Planning and Standards 2011, US Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards 2015). The VSL for $PM_{2.5}$-related mortality is $8.5 million; the VSL for an ozone-related mortality case is $9.4 million, since there is not a significant lag between ozone exposure and mortality. We calculate the stream of health benefits both undiscounted and discounted at 3% yr^{-1}, to be consistent with the values used in the SCC. All monetary values are presented in 2017 USD.
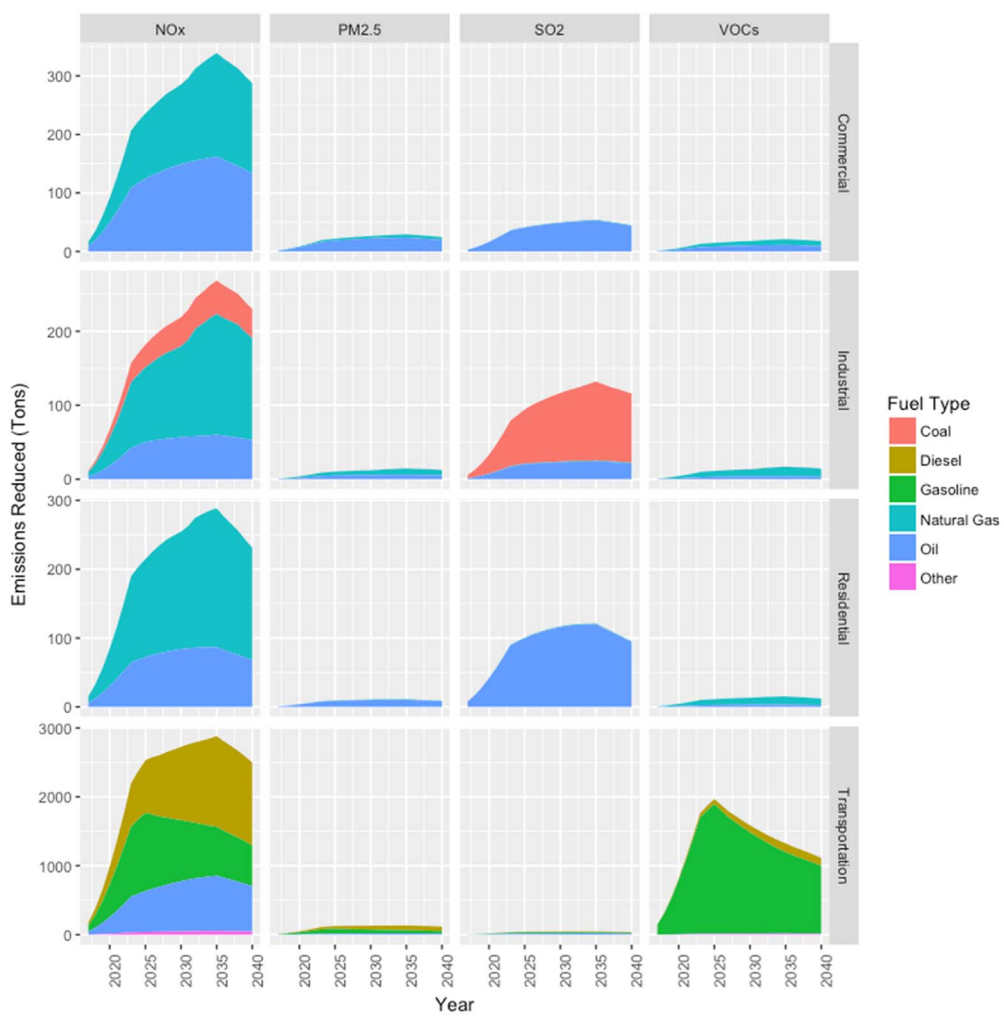
Results

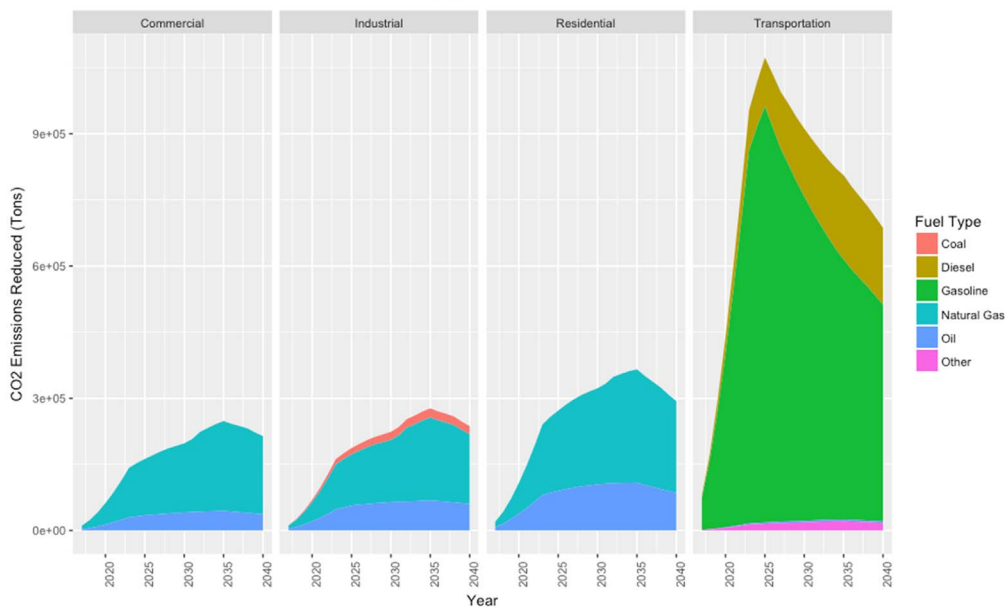**Changes in fuel use and emissions reductions**
Transportation had the highest reduction in energy use, followed by residential buildings. Gasoline was the fuel type with the highest reduction in use, followed by natural gas (figure 2). Reductions vary over time given the increasing carbon price through 2023, with differential responses to rising carbon prices among sectors. Peak reductions in motor vehicle gasoline use occur in 2025 and begin to

decrease after 2025. For other affected sources, this peak occurs in 2035 (figure 2).

The air pollutant with the most reductions is NO_x, followed by VOCs (figure 3(a)). Reductions in all air pollution emissions except VOCs grow rapidly until 2023, grow more slowly between 2023 and 2025, plateau or decrease between 2025 and 2035 (figure 3(a)); VOCs reach their peak in reduction in 2025 and taper off afterwards (figure 3(a)). The CO_2 reductions follow a time trend where they reach a peak in 2025, plateau from 2025 to 2035, and then begin to taper off after 2035 (figure 3(b)). Reductions in NO_x and primary $PM_{2.5}$ emissions are largely from reduced use of gasoline, oil, and diesel in the transportation sector (figure 3(a)). Reductions in SO_2 are largely from reduced oil use in residential and commercial buildings, and from reduced coal use in the industrial sector (figure 3(a)). VOC reductions are mostly from reduced gasoline use in the transportation sector (figure 3(a)). CO_2 emissions reductions are largely driven by reductions in gasoline use in the transportation sector from implementation to 2025 (figure 3(b)). CO_2 reductions from gasoline use taper off after 2025, while reductions from reduced natural gas use grow, becoming roughly equal to reductions from gasoline use in 2035 (figure 3(b)).

Figure 3. (a): Emissions reductions of NO_x, $PM_{2.5}$, SO_2, and VOCs due to a model carbon fee between 2017 and 2040, by source sector and fuel type. (b): Emissions reductions of CO_2 due to a model carbon fee between 2017–2040, by source sector and fuel type.
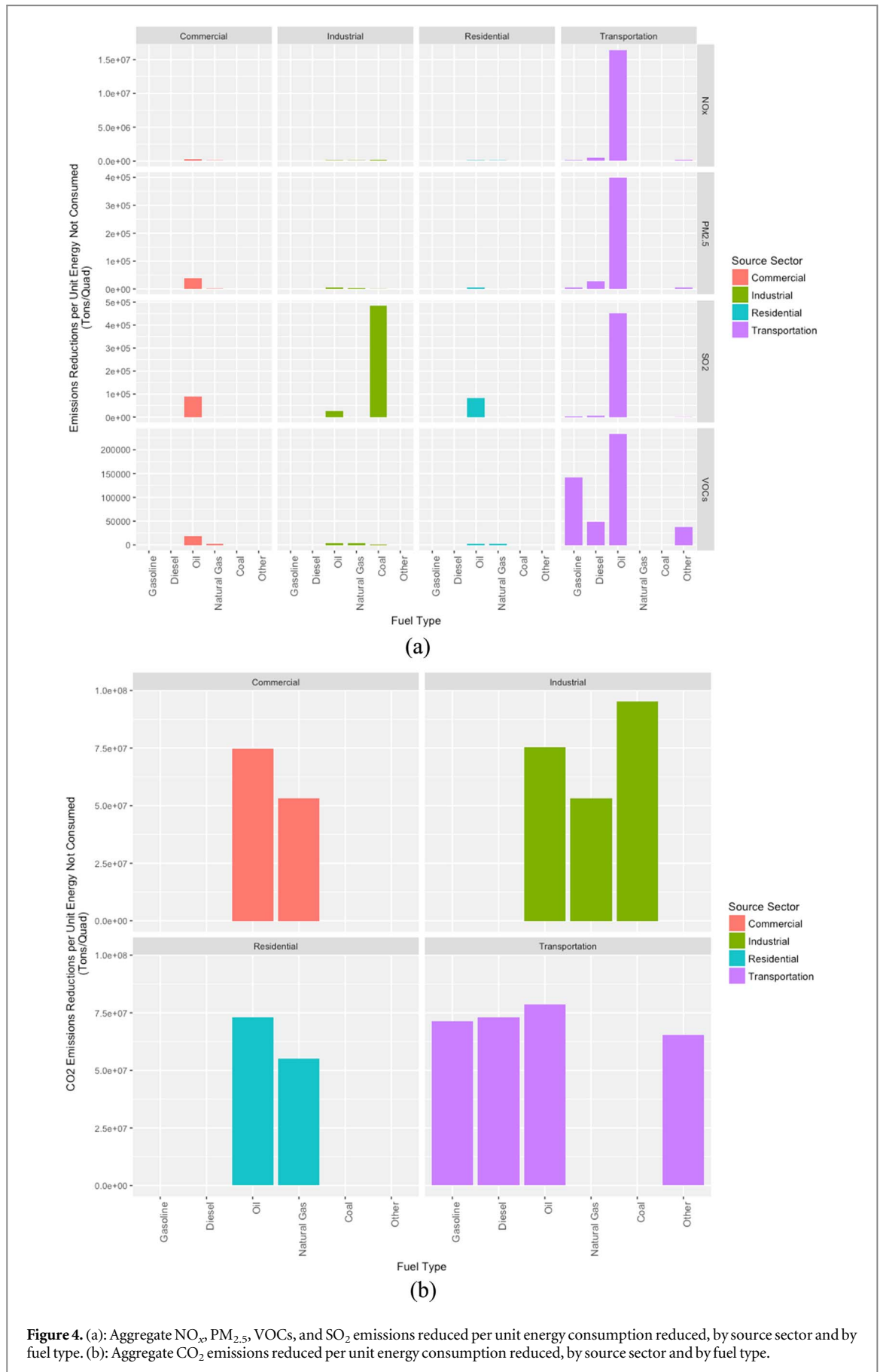
(a)

(b)

Figure 4. (a): Aggregate NO_x, $PM_{2.5}$, VOCs, and SO_2 emissions reduced per unit energy consumption reduced, by source sector and by fuel type. (b): Aggregate CO_2 emissions reduced per unit energy consumption reduced, by source sector and by fuel type.

Table 1. Total climate and health benefits of a carbon fee and rebate policy in Massachusetts from 2017–2040.

Benefit type	Benefits (95% CI)
Total lives saved	340 (82–590)
Value of health benefits, undiscounted	$2.9 billion ($0.66–$5.2 billion)
Value of health benefits, discounted at 3% yr^{-1}	$2.0 billion ($0.45–$3.5 billion)
Total reductions in CO_2 emissions	33 million metric tons
Value of climate benefits, undiscounted	$2.0 billion
Value of climate benefits, discounted at 3% yr^{-1}	$1.3 billion

Emissions avoided per unit of energy use reduced are very high for the use of oil in transportation, and high across all other sectors (figure 4(a)). Coal has the highest SO_2 emissions reductions per unit energy reduced (figure 4(a)). Gasoline and diesel use in the transportation sector also had fairly high VOC emissions avoided per unit energy reduced (figure 4(a)). CO_2 reductions per unit of energy reductions are much more even across fuel types and source sectors than for air pollutants (figure 4(b)).

Health and climate benefits

Between 2017–2040, this policy saves approximately 340 (95% CI: 82–590) lives (table 1, figure 5). The health benefits roughly parallel emissions reductions over time, with a value of $2.9 billion (95% CI: $0.71–$5.2 billion) undiscounted, and a value of $2.0 billion ($0.49–$3.5 billion) when discounted at 3% yr^{-1} (table 1, figure 6). The health benefits of this policy are mainly driven by NO_x reductions contributing to both ozone and $PM_{2.5}$, primary $PM_{2.5}$, and emissions from VOCs, which contribute to both $PM_{2.5}$ and ozone formation (figure 5). Reductions in SO_2 emissions had a comparatively small contribution (figure 5). Emissions reductions in the transportation sector were the largest contributor (85%) to total health benefits, with health benefits initially driven by reductions in gasoline, but gradually becoming nearly evenly split among diesel, gasoline, and oil as the carbon fee goes into effect (figure 5, table 2). The lives saved mainly occurred within Massachusetts, with 63%, and in the surrounding states–12% in New Hampshire, 8% in New York, 4% in Rhode Island, 4% in Connecticut, 4% in New Jersey, and 2% in Maine (table 2).

Reduction in oil use, largely in buildings and in transportation, also contributed highly to health benefits. Reductions in NO_x emissions from buildings, largely from lesser oil and natural gas use, predominantly occurred in the winter and produced slight increases in ozone. This slightly reduced the total health co-benefits (figure 5). Reduced oil consumption for transportation also generally has the highest lives saved per unit of energy reduced, especially in transportation, but reduced coal use in industry is also high, largely driven

by SO_2 reductions (figure 7). When monetized, oil generally has the highest benefits per unit of energy consumption reduced, especially in transportation. Between 2017–2040, the policy would reduce CO_2 emissions by approximately 33 million metric tons (figure 2(b)). The CO_2 reductions have a value of $2.0 billion undiscounted, and $1.3 billion when discounted at 3% yr^{-1} (table 1, figure 2(b)).

The monetized benefits are slightly higher for health than for climate, with marked variation across sectors and fuel types (table 1, figure 6). The monetized benefits are largely driven by transportation, followed by the buildings sectors. The benefits of reduced fuel consumption in transportation were driven by health, with a more even split between health and climate for commercial buildings. Residential and industrial benefits were mostly based on greenhouse gas mitigation (figure 6). Across fuel types, the leading contributor to benefits is reductions in gasoline use, followed by diesel, oil and natural gas (figure 6). Health benefits generally contributed more to total benefits than climate for gasoline, diesel, and oil, while climate benefits were greater for natural gas than health (figure 6).

Discussion

A model carbon fee-and-rebate bill in the state of Massachusetts would advance greenhouse gas emissions' reductions, while providing substantive, health gains, mainly within state, that have comparable magnitude to the climate benefits when monetized.

The peak reductions occur after the peak price due to the time required for turnover, which is longer for buildings than the vehicle fleet. Reductions in fuel consumption and pollutant emissions reach a plateau and then fall since the model carbon fee is not tied to inflation.

Our results here indicate that when monetized, the health benefits are fairly similar in magnitude to the climate benefits, comparable to findings in previous studies focusing on renewable energy and energy efficiency (Siler-Evans *et al* 2012, 2013, Buonocore *et al* 2015, 2016b, Levy *et al* 2016). Between 2017–2040, this policy has approximately $88 in health benefits per ton of CO_2 reduced, and saves 10.3 lives per million tons of CO_2 reduced, similar to estimates from an economy-wide cap-and-trade program implemented in the northeast US (Thompson *et al* 2016), and slightly higher than a carbon standard in the electrical sector in the US (Driscoll *et al* 2015).

The model framework developed here has a number of limitations. The CTAM model does not fully capture spillover effects (like purchasing fuel out-of-state), effects of technology change, or effects of future regulations. There are a number of actions that can be taken to reduce emissions, including transportation mode-shifting, purchasing vehicles with higher fuel
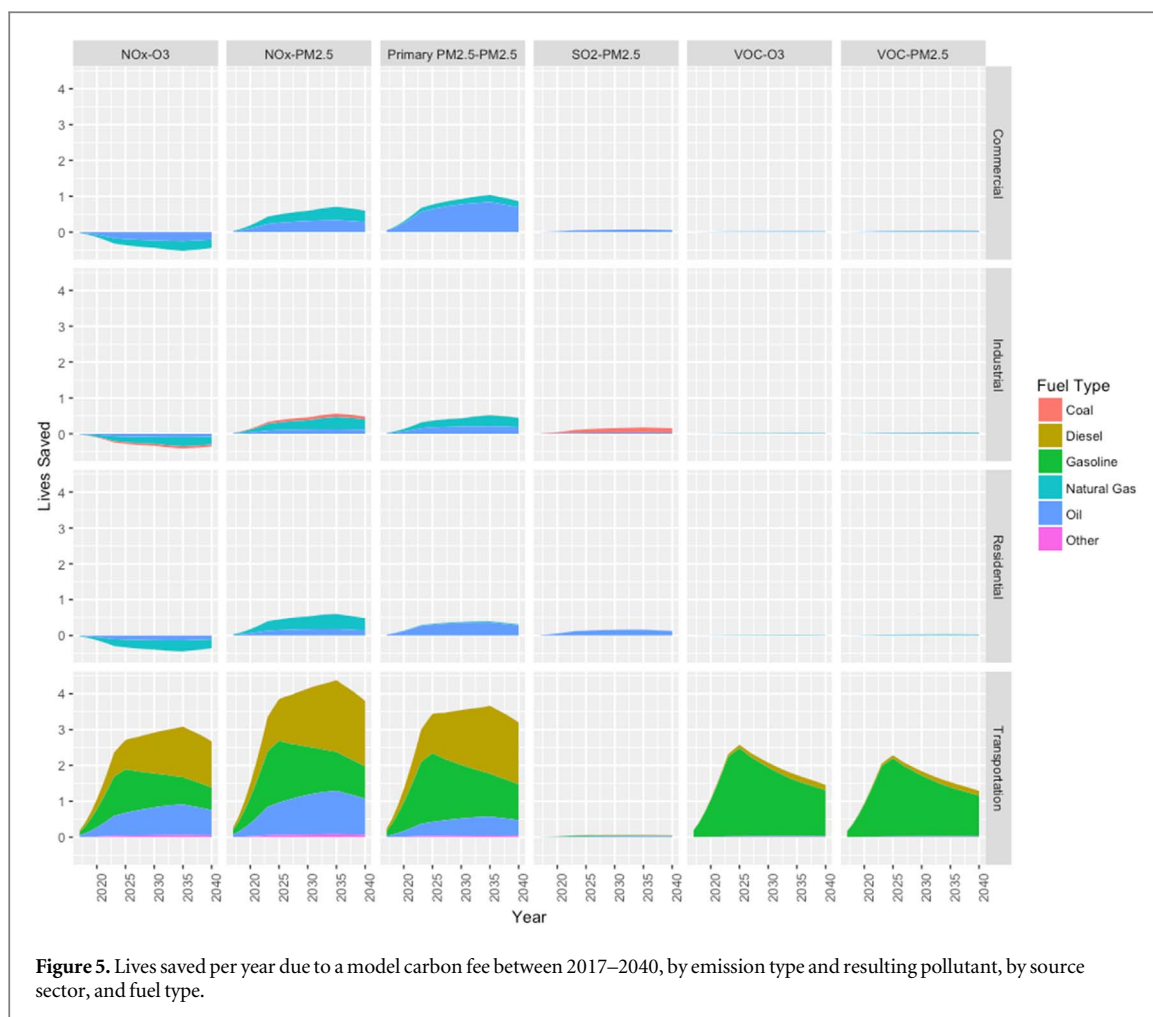
Figure 5. Lives saved per year due to a model carbon fee between 2017–2040, by emission type and resulting pollutant, by source sector, and fuel type.

economy, and energy efficiency in buildings, but CTAM also does not model how the changes in fuel demand are being implemented, what the costs are, and which actors incur those costs (Washington State Department of Commerce n.d., Breslow *et al* 2014). CTAM does employ a lag structure in the price elasticity, so it is able to appropriately reflect longer-term changes due to, for example, turnover time of building stock or vehicle fleet (Washington State Department of Commerce n.d., Breslow *et al* 2014). Since CTAM does not explicitly model how the reductions in fuel use are occurring, it cannot model what changes are temporary and reversible, like switching from driving a personal vehicle to using public transportation or maintaining buildings at a lower indoor temperature; or permanent, like purchasing a more fuel-efficient vehicle or improving home insulation (Washington State Department of Commerce n.d., Breslow *et al* 2014). Future changes in emissions due to air quality regulations, changes in combustion efficiency or fuel mix, changes in the use of air pollution controls or other technology changes are not captured. While the use of CTAM and reliance on emissions from NEI may not capture all relevant economic, regulatory, and technological effects that may determine emissions reductions and health gains from a carbon price, the basic framework does reasonably at capturing the

main drivers of the benefits of a carbon fee-and-rebate policy, including economic effects associated with price elasticity (Nystrom and Zaidi 2013, Breslow *et al* 2014). This modeling framework here is fairly similar to the economic modeling in previous studies (Thompson *et al* 2016, Li *et al* 2018). Although these studies contain more explicit linkages to other elements of the economy, linkages to trade, and other economic factors, while the model used here exclusively uses in-state changes (Thompson *et al* 2016, Li *et al* 2018). Use of CTAM alone is also insufficient to understand broader economic impact of a carbon policy, in part, because the economic effects of a carbon price depend on what is done with the revenue (Nystrom and Zaidi 2013, Breslow *et al* 2014, Ambasta and Buonocore 2018, California Air Resources Board 2018).

Our health model operates at state-level resolution with average values for winter and summer, so may not perfectly capture effect variability due to population proximity to sources, timing of emissions, or changes in population or baseline population health status over time. Across Massachusetts, the county-level mortality rate varies by a factor of two (872 to 1662 per 100 000), and the social costs of NO_x, SO_2, and $PM_{2.5}$ emissions also do not vary substantially (Centers for Disease Control and Prevention n.d., Heo
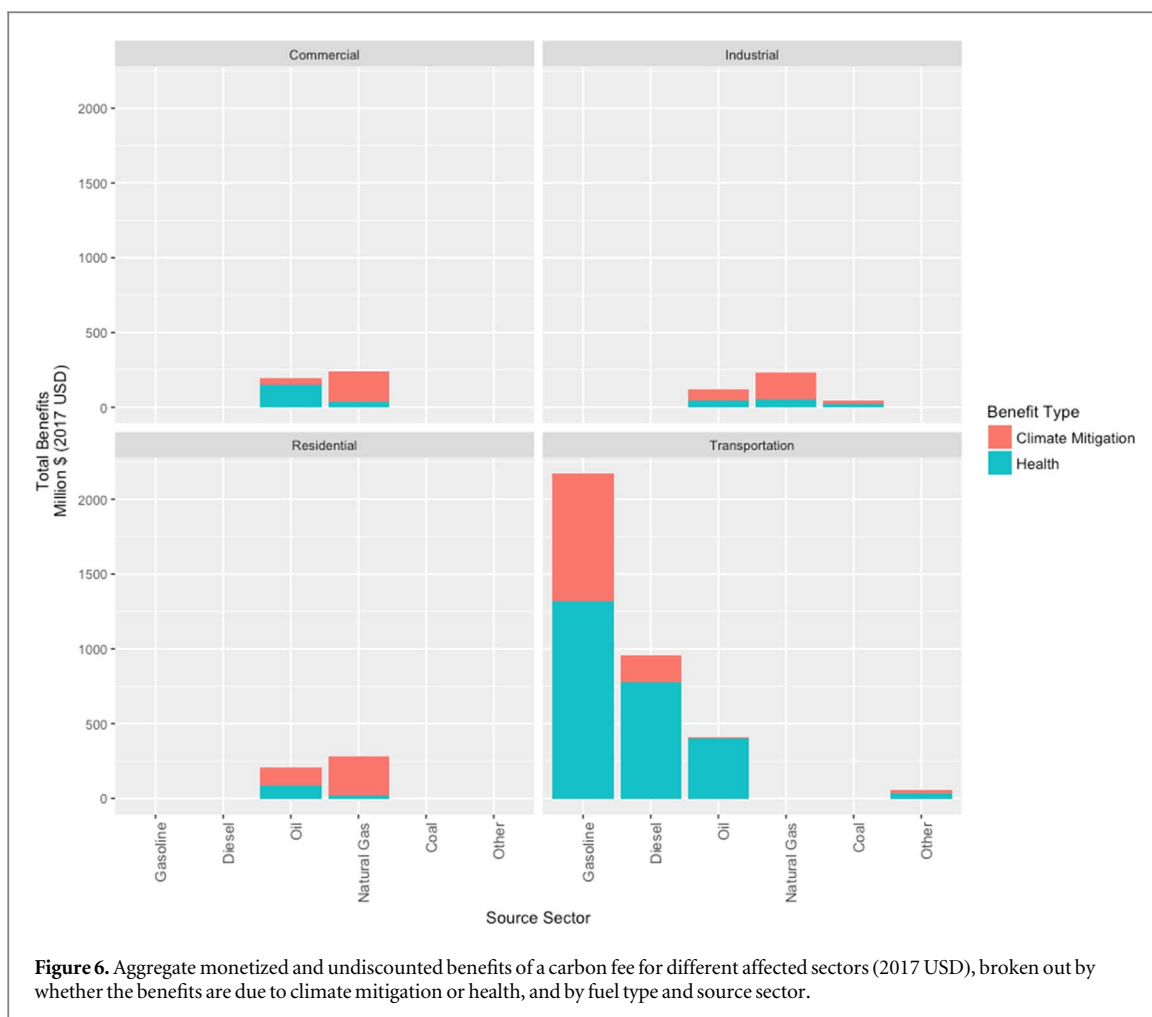
Figure 6. Aggregate monetized and undiscounted benefits of a carbon fee for different affected sectors (2017 USD), broken out by whether the benefits are due to climate mitigation or health, and by fuel type and source sector.

Table 2. Proportion of health benefits from air pollution reductions from a carbon fee and rebate policy in Massachusetts from 2017–2040, by state and by source sector.

Source sector	Total lives saved in all states	Percentage of source sector benefits occurring within state							
		MA	NH	NY	RI	CT	NJ	ME	All others
Commercial	7%	57%	14%	10%	4%	5%	4%	4%	2%
Industrial	4%	54%	14%	11%	4%	5%	5%	4%	2%
Residential	4%	51%	14%	12%	4%	5%	6%	4%	3%
Transportation	85%	65%	12%	7%	4%	4%	3%	2%	3%
Total from all sectors		63%	12%	8%	4%	4%	4%	2%	3%

et al 2016a, 2016b). The model may still not perfectly capture possible geographical clustering of emissions reductions and areas with high population or more vulnerable populations, introducing some uncertainty. Additionally, the use of residential combustion impact-per-ton values is an imperfect proxy for transportation-related emissions, but the county-level emissions from each source type are reasonably correlated (Pearson correlation coefficients: 0.65 for SO_2, 0.71 for VOCs, 0.73 for $PM_{2.5}$, and 0.98 for NO_x).

Using emissions and impact rates from a historical base year to estimate the impacts of future changes in air pollution is common (Buonocore *et al* 2014, 2015, 2016a, 2016b, Driscoll *et al* 2015, Levy *et al* 2016, Heo *et al* 2016a, 2016b, 2017, Penn *et al* 2017).

Ignoring population growth and aging would likely result in an underestimate of benefits. Technology changes over time could result in reduced emissions per unit energy and a corresponding overestimate of the total climate and health benefits. The model framework employed here does not have as high spatial and temporal resolution as other research, but our impact-per-ton functions are based on an advanced atmospheric modeling platform and allow for decomposition of benefits by sector and by emission type.

This analysis excludes several morbidities associated with air pollution including, like cardiovascular and respiratory disease, asthma, heart attacks, stroke, premature birth, low birth weight, lost days of school and work, and neurocognitive diseases (Gilliland *et al*
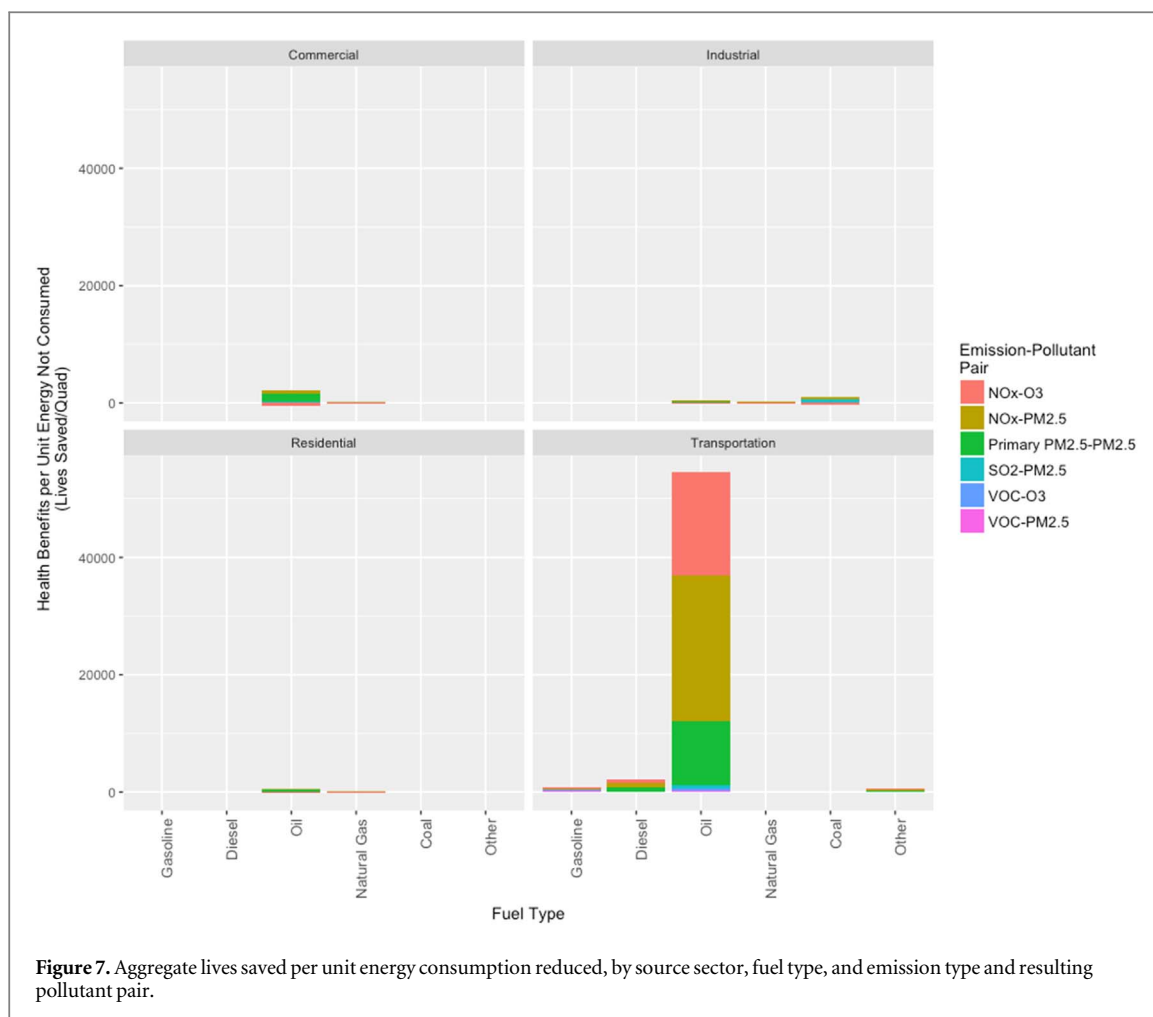
Figure 7. Aggregate lives saved per unit energy consumption reduced, by source sector, fuel type, and emission type and resulting pollutant pair.

2001, Zanobetti and Schwartz 2009, Zanobetti *et al* 2009, Darrow *et al* 2010, Anderson *et al* 2011, Mustafić *et al* 2012, Levy *et al* 2012, Kloog *et al* 2012, Madrigano *et al* 2013, Jacquemin *et al* 2015, Talbott *et al* 2015, Jung *et al* 2015, Li *et al* 2016, Chen *et al* 2017, Cacciottolo *et al* 2017). We also do not include ecological benefits of reduced air pollution, like increased productivity for crops and timber, and decreases in eutrophication (Jaworski *et al* 1997, Aldy and Kramer 1999, Wittig *et al* 2007, Van Dingenen *et al* 2009), or health impacts from the reduction in hazardous air pollutant (Sunderland *et al* 2016). We also do not include other health and environmental impacts of extraction of the fuels whose use is avoided, including methane leaks from natural gas infrastructure, strain on underground natural gas storage facilities, air and water pollution and consequent health impacts from natural gas extraction, and possible impacts from accidents in oil and gas extraction or transportation (Adgate *et al* 2014, Brandt *et al* 2014, McKenzie *et al* 2014, Subramanian *et al* 2015, Brandt *et al* 2016, Peres *et al* 2016, Torres *et al* 2016, Butkovskyi *et al* 2017, Harriman *et al* 2017, Michanowicz *et al* 2017).

The climate benefits may be quite sensitive to methane leakage across the natural gas supply chain. A leak rate of 2.3% and a social cost of methane of $1200 per ton would result in an additional ~$138 million in

benefits from climate mitigation, increasing the total benefits due to reduction in natural gas consumption by around 18% (Interagency Working Group on Social Cost of Carbon 2016, Phillips *et al* 2013, Alvarez *et al* 2018). Using the global average social cost of methane of $4600 per ton, which incorporates health impacts, makes benefits of reduced leakage closer to $530 million, or a 31% higher (Shindell 2015). Higher leakage rates, or higher weighting of near-term climate impacts would increase this sensitivity substantially. Our SCC may be an underestimate, as it may miss some important health impacts, effects on economic growth, and not appropriately deal with the distribution of climate impacts across space or time (Arrow *et al* 2013, Diaz and Moore 2017).

This study adds to existing literature on the health co-benefits of efforts to mitigate climate change. We examine the effects of a multi-sector fee-and-dividend bill, not including electricity, whereas much of the existing health co-benefits literature applies to electricity generation. It also examines an individual state plan, as opposed to regional or national policies. That said, the benefits of applying a carbon price to electricity generation can be around 3.9 lives per million tons of CO_2 emissions reduced (Driscoll *et al* 2015). Another study examining nationwide clean energy standards found that the value of the health benefits

can exceed the policy implementation costs (Thompson *et al* 2014).

With two years remaining to change the global trajectory of carbon emissions to meet the goals set forward by the Paris Agreement (Figueres *et al* 2017), and the US having announced its intent to leave the agreement (Tollefson 2017), regional, state, and local carbon pricing initiatives have become more important to the nation as a whole (Hepburn 2017). Understanding the health co-benefits of different policy options can aid in the design of policies, help incentivize their implementation (Petrovic *et al* 2014, Bain *et al* 2015), and help sub-national governments contribute to the world achieving the goals of the Paris Agreement.

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References

Adgate J L, Goldstein B D and McKenzie L M 2014 Potential public health hazards, exposures and health effects from unconventional natural gas development *Environ. Sci. Technol.* **48** 8307–20

Aldy J E and Kramer R A 1999 Environmental equity and the conservation of unique ecosystems: an analysis of the distribution of benefits for protecting southern appalachian spruce-fir forests *Soc. Nat. Resour.* **12** 93–106

Alvarez R A *et al* 2018 Assessment of methane emissions from the U.S. oil and gas supply chain *Science* **361** 186–8

Ambasta A and Buonocore J J 2018 Carbon pricing: a win-win environmental and public health policy *Can. J. Public Health* 1–3 (https://doi.org/10.17269/s41997-018-0099-5)

Anderson H R, Favarato G and Atkinson R W 2011 Long-term exposure to air pollution and the incidence of asthma: meta-analysis of cohort studies *Air Qual. Atmos. Health* **6** 47–56

Appel K W *et al* 2017 Description and evaluation of the Community Multiscale Air Quality (CMAQ) modeling system version 5.1 *Geosci. Model Dev.* **10** 1703–32

Arrow K *et al* 2013 Determining benefits and costs for future generations *Science* **341** 349–50

Arunachalam S, Wang– B, Davis N, Baek B H and Levy J I 2011 Effect of chemistry-transport model scale and resolution on population exposure to PM2.5 from aircraft emissions during landing and takeoff *Atmospheric Environ.* **45** 3294–300

Bain P G *et al* 2015 Co-benefits of addressing climate change can motivate action around the world *Nat. Clim. Change* **5** 226

Barrett M J An Act Combating Climate Change (https://malegislature.gov/Bills/190/SD1021/District)

Bell M L 2004 Ozone and short-term mortality in 95 US urban communities, 1987–2000 *J. Am. Med. Assoc.* **292** 2372

Bell M L, Dominici F and Samet J M 2005 A meta-analysis of time-series studies of ozone and mortality with comparison to the national morbidity, mortality, and air pollution study *Epidemiology* **16** 436–45

Benson J E An Act to Promote Green Infrastructure, Reduce Greenhouse Gas Emissions, and Create Jobs (https://malegislature.gov/Bills/190/H1726)

Bergin M S, Russell A G, Odman M T, Cohan D S and Chameides W L 2012 Single-source impact analysis using three-dimensional air quality models *J. Air Waste Manage. Assoc.* **58** 1351–9

Brandt A R, Heath G A and Cooley D 2016 Methane leaks from natural gas systems follow extreme distributions *Environ. Sci. Technol.* **50** 12512–20

Brandt A R *et al* 2014 Methane leaks from north american natural gas systems *Science* **343** 733–5

Breslow M, Hamel S, Luckow P and Nystrom S 2014 Analysis of a Carbon Fee or Tax as a Mechanism to Reduce GHG Emissions in Massachusetts (http://mass.gov/eea/docs/doer/fuels/mass-carbon-tax-study.pdf)

Buonocore J J, Dong X, Spengler J D, Fu J S and Levy J I 2014 Using the community multiscale air quality (CMAQ) model to estimate public health impacts of PM2.5 from individual power plants *Environ. Int.* **68** 200–8

Buonocore J J, Lambert K F, Burtraw D, Sekar S and Driscoll C T 2016a An analysis of costs and health co-benefits for a US Power Plant carbon standard *PLoS One* **11** e0156308

Buonocore J J, Luckow P, Fisher J, Kempton W and Levy J I 2016b Health and climate benefits of offshore wind facilities in the Mid-Atlantic United States *Environ. Res. Lett.* **11** 074019

Buonocore J J, Luckow P, Norris G, Spengler J D, Biewald B, Fisher J and Levy J I 2015 Health and climate benefits of different energy-efficiency and renewable energy choices *Nat. Clim. Change* **6** 100–5

Butkovskyi A, Bruning H, Kools S A E, Rijnaarts H H M and van Wezel A P 2017 Organic pollutants in shale gas flowback and produced waters: identification, potential ecological impact, and implications for treatment strategies *Environ. Sci. Technol.* **51** 4740–54

Byun D and Schere K L 2006 Review of the Governing Equations, Computational Algorithms, and Other Components of the Models-3 Community Multiscale Air Quality (CMAQ) Modeling System *Appl. Mech. Rev.* **59** 51–27

Cacciottolo M *et al* 2017 Particulate air pollutants, APOE alleles and their contributions to cognitive impairment in older women and to amyloidogenesis in experimental models *Transl. Psychiatry* **7** e1022

Caiazzo F, Ashok A, Waitz I A, Yim S H L and Barrett S R H 2013 Air pollution and early deaths in the United States: I. Quantifying the impact of major sectors in 2005 *Atmos. Environ.* **79** 198–208

California Air Resources Board 2018 California Climate Investments Using Cap-and-Trade Auction Proceeds (https://arb.ca.gov/cc/capandtrade/auctionproceeds/2018_cci_annual_report.pdf)

Centers for Disease Control and Prevention CDC Wonder (https://wonder.cdc.gov)

Chen H *et al* 2017 Exposure to ambient air pollution and the incidence of dementia: a population-based cohort study *Environ. Int.* **108** 271–7

Cohan D S, Hakami A, Hu Y and Russell A G 2005 Nonlinear response of ozone to emissions: source apportionment and sensitivity analysis *Environ. Sci. Technol.* **39** 6739–48

Darrow L A, Klein M, Strickland M J, Mulholland J A and Tolbert P E 2010 Ambient air pollution and birth weight in full-term infants in atlanta, 1994–2004 *Environ. Health Perspect.* **119** 731–7

Diaz D and Moore F 2017 Quantifying the economic risks of climate change *Nat. Clim. Change* **7** 3411–782

Dockins C, Maguire K, Simon N and Sullivan M 2004 *Value of Statistical Life Analysis and Environmental Policy* A White Paper pp 1–25

Driscoll C T, Buonocore J J, Levy J I, Lambert K F, Burtraw D, Reid S B, Fakhraei H and Schwartz J 2015 US power plant carbon standards and clean air and health co-benefits *Nat. Clim. Change* **5** 535–40

Fann N, Lamson A D, Anenberg S C, Wesson K, Risley D and Hubbell B J 2011 Estimating the National Public Health Burden Associated with Exposure to Ambient PM2.5 and Ozone *Risk Analysis* **32** 81–95

Figueres C, Schellnhuber H J, Whiteman G, Rockström J, Hobley A and Rahmstorf S 2017 Three years to safeguard our climate *Nature* **546** 593–5

Foley K M *et al* 2010 Incremental testing of the Community Multiscale Air Quality (CMAQ) modeling system version 4.7 *Geosci. Model Dev.* **3** 205–26

Gilliland F D *et al* 2001 The effects of ambient air pollution on school absenteeism due to respiratory illnesses *Epidemiology* **12** 43–54

Haines A 2017 Health co-benefits of climate action *Lancet Planet. Health* **1** e4–5

Harriman B H, Zito P, Podgorski D C, Tarr M A and Suflita J M 2017 Impact of photooxidation and biodegradation on the fate of oil spilled during the deepwater horizon incident: advanced stages of weathering *Environ. Sci. Technol.* **51** 7412–21

Heo J, Adams P J and Gao H O 2017 Public health costs accounting of inorganic $PM_{2.5}$ pollution in metropolitan areas of the United States using a risk-based source-receptor model *Environ. Int.* **106** 119–26

Heo J, Adams P J and Gao H O 2016a Public health costs of primary $PM_{2.5}$ and Inorganic $PM_{2.5}$ precursor emissions in the United States *Environ. Sci. Technol.* **50** 6061–70

Heo J, Adams P J and Gao H O 2016b Reduced-form modeling of public health impacts of inorganic $PM_{2.5}$ and precursor emissions *Atmos. Environ.* **137** 80–9

Hepburn C 2017 Climate change economics: make carbon pricing a priority *Nat. Clim. Change* **7** 389–90

Interagency Working Group on Social Cost of Carbon 2016 Technical Support Document: - Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis— Under Executive Order 12866 (https://epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf)

Itahashi S, Uno I and Kim S 2012 Source contributions of sulfate aerosol over east asia estimated by CMAQ-DDM *Environ. Sci. Technol.* **46** 6733–41

Jacquemin B *et al* 2015 Ambient air pollution and adult asthma incidence in six european cohorts (ESCAPE) *Environ. Health Perspect.* **123** 613–21

Jaworski N A, Howarth R W and Hetling L J 1997 Atmospheric deposition of nitrogen oxides onto the landscape contributes to coastal eutrophication in the Northeast United States *Environ. Sci. Technol.* **31** 1995–2004

Jung C-R, Lin Y-T and Hwang B-F 2015 Ozone, particulate matter, and newly diagnosed Alzheimer's disease: a population-based cohort study in Taiwan *J. Alzheimers Dis.* **44** 573–84

Kloog I, Coull B A, Zanobetti A, Koutrakis P and Schwartz J D 2012 Acute and chronic effects of particles on hospital admissions in New-England ed M B Gravenor *PLoS One* **7** e34664

Lepeule J, Laden F, Dockery D and Schwartz J 2012 Chronic exposure to fine particles and mortality: an extended follow-up of the harvard six cities study from 1974 to 2009 *Environ. Health Perspect.* **120** 965–70

Levy J I, Diez D, Dou Y, Barr C D and Dominici F 2012 A meta-analysis and multisite time-series analysis of the differential toxicity of major fine particulate matter constituents *Am. J. Epidemiol.* **175** 1091–9

Levy J I, Woo M K, Penn S L, Omary M, Tambouret Y, Kim C S and Arunachalam S 2016 Carbon reductions and health co-benefits from US residential energy efficiency measures *Environ. Res. Lett.* **11** 034017

Li L, Laurent O and Wu J 2016 Spatial variability of the effect of air pollution on term birth weight: evaluating influential factors using Bayesian hierarchical models *Environ. Health* **15** 9

Li M, Zhang D, Li C-T, Mulvaney K M, Selin N E and Karplus V J 2018 Air quality co-benefits of carbon pricing in China *Nat. Clim. Change* **32** 567

Madrigano J, Kloog I, Goldberg R, Coull B A, Mittleman M A and Schwartz J 2013 Long-term exposure to $PM_{2.5}$ and incidence of acute myocardial infarction *Environ. Health Perspect.* **121** 192–6

McKenzie L M, Guo R, Witter R Z, Savitz D A, Newman L S and Adgate J L 2014 Birth outcomes and maternal residential proximity to natural gas development in rural colorado *Environ. Health Perspect.* **122** 412–7

Michanowicz D R, Buonocore J J, Rowland S T, Konschnik K E, Goho S A and Bernstein A S 2017 A national assessment of underground natural gas storage: identifying wells with designs likely vulnerable to a single-point-of-failure *Environ. Res. Lett.* **12** 064004

Mittal S, Hanaoka T, Shukla P R and Masui T 2015 Air pollution co-benefits of low carbon policies in road transport: a sub-national assessment for India *Environ. Res. Lett.* **10** 085006

Mustafić H *et al* 2012 Main air pollutants and myocardial infarction *J. Am. Med. Assoc.* **307** 713

Napelenok S L, Cohan D S, Hu Y and Russell A G 2006 Decoupled direct 3D sensitivity analysis for particulate matter (DDM-3D/PM) *Atmos. Environ.* **40** 6112–21

Nemet G F, Holloway T and Meier P 2010 Implications of incorporating air-quality co-benefits into climate change policymaking *Environ. Res. Lett.* **5** 014007

Nystrom S and Zaidi A 2013 Modeling the Economic, Demographic, and Climate Impact of a Carbon Tax in Massachusetts (http://remi.com/wp-content/uploads/2017/12/20-Modeling-the-Economic-Demographic-and-Climate-Impact-of-a-Carbon-Tax-in-Massachusetts.pdf)

Penn S L, Arunachalam S, Woody M, Heiger-bernays W, Tripodis Y and Levy J I 2017 Estimating state-specific contributions to $PM_{2.5}$- and O_3-related health burden from residential combustion and electricity generating unit emissions in the United States *Environ. Health Perspect.* **125** 324–32

Peres L C, Trapido E, Rung A L, Harrington D J, Oral E, Fang Z, Fontham E and Peters E S 2016 The deepwater horizon oil spill and physical health among adult women in southern louisiana: the women and their children's health (WaTCH) study *Environ. Health Perspect.* **124** 1208–13

Perry I, Veung C and Heine D 2014 *How Much Carbon Pricing is in Countries' Own Interests? The Critical Role of Co-Benefits* (White Paper) World Bank (https://www.imf.org/external/pubs/ft/wp/2014/wp14174.pdf)

Petrovic N, Madrigano J and Zaval L 2014 Motivating mitigation: when health matters more than climate change *Clim. Change* **126** 245–54

Phillips N G, Ackley R, Crosson E R, Down A, Hutyra L R, Brondfield M, Karr J D, Zhao K and Jackson R B 2013 Mapping urban pipeline leaks: Methane leaks across Boston *Enviro. Pollution* **173** 1–4

Plachinski S D, Holloway T, Meier P J, Nemet G F, Rrushaj A, Oberman J T, Duran P L and Voigt C L 2014 Quantifying the emissions and air quality co-benefits of lower-carbon electricity production *Atmos. Environ.* **94** 180–91

Roman H A, Walker K D, Walsh T L, Conner L, Richmond H M, Hubbell B J and Kinney P L 2008 Expert judgment assessment of the mortality impact of changes in ambient fine particulate matter in the US *Environ. Sci. Technol.* **42** 2268–74

Roy B, Mathur R, Gilliland A B and Howard S C 2007 A comparison of CMAQ-based aerosol properties with IMPROVE, MODIS, and AERONET data *J. Geophys. Res.* **112** 1–17

Saari R K, Selin N E, Rausch S and Thompson T M 2014 A self-consistent method to assess air quality co-benefits from US climate policies *J. Air Waste Manage. Assoc.* **65** 74–89

Sanderson B M and Knutti R 2016 Delays in US mitigation could rule out Paris targets *Nat. Clim. Change* **7** 92–4

Schwartz J 2005 How sensitive is the association between ozone and daily deaths to control for temperature? *Am. J. Respir. Crit. Care Med.* **171** 627–31

Shindell D T 2015 The social cost of atmospheric release *Clim. Change* **130** 313–26

Siler-Evans K, Azevedo I L and Morgan M G 2012 Marginal emissions factors for the US electricity system *Environ. Sci. Technol.* **46** 4742–8

Siler-Evans K, Azevedo I L, Morgan M G and Apt J 2013 Regional variations in the health, environmental, and climate benefits of wind and solar generation *Proc. Natl Acad. Sci. USA* **110** 11768–73

Stackelberg von K, Buonocore J, Bhave P V and Schwartz J A 2013 Public health impacts of secondary particulate formation from aromatic hydrocarbons in gasoline *Environ. Health* **12** 19

Subramanian R *et al* 2015 Methane emissions from natural gas compressor stations in the transmission and storage sector: measurements and comparisons with the EPA greenhouse gas reporting program protocol *Environ. Sci. Technol.* **49** 3252–61

Sunderland E M *et al* 2016 Benefits of regulating hazardous air pollutants from coal and oil-fired utilities in the United States *Environ. Sci. Technol.* **50** 2117–20

Talbott E O, Arena V C, Rager J R, Clougherty J E, Michanowicz D R, Sharma R K and Stacy S L 2015 Fine particulate matter and the risk of autism spectrum disorder *Environ. Res.* **140** 414–20

The World Bank Carbon Pricing Dashboard (https://carbonpricingdashboard.worldbank.org)

Thompson T M, Rausch S, Saari R K and Selin N E 2014 A systems approach to evaluating the air quality co-benefits of US carbon policies *Nat. Clim. Change* **4** 917–23

Thompson T M, Rausch S, Saari R K and Selin N E 2016 Air quality co-benefits of subnational carbon policies *J. Air Waste Manage. Assoc.* **66** 988–1002

Thompson T M and Selin N E 2012 Influence of air quality model resolution on uncertainty associated with health impacts *Atmos. Chem. Phys.* **12** 9753–62

Tollefson J 2017 Trump pulls United States out of Paris climate agreement *Nature* **546** 198–198

Torres L, Yadav O P and Khan E 2016 A review on risk assessment techniques for hydraulic fracturing water and produced water management implemented in onshore unconventional oil and gas production *Sci. Total Environ.* **539** 478–93

US Energy Information Administration 2018 Monthly Energy Review (https://eia.gov/totalenergy/data/monthly/)

US Environmental Protection Agency 2017 Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2015—Main Text (https://epa.gov/sites/production/files/2017-02/documents/2017_complete_report.pdf)

US Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards 2015 Regulatory Impact Analysis for the Clean Power Plan Final Rule vol 314 (https://3.epa.gov/ttnecas1/docs/ria/utilities_ria_final-clean-power-plan-existing-units_2015-08.pdf)

US Environmental Protection Agency Office of Air Quality Planning and Standards 2011 Regulatory Impact Analysis for the Final Mercury and Air Toxics Standards(https://www3.epa.gov/ttnecas1/regdata/RIAs/matsriafinal.pdf)

US Enviromental Protection Agency 2012 *Air Quality Modeling Technical Support Document: 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards Final Rule* Office of Transportation and Air Quality, Air Quality Assessment Division pp 1–153 (EPA-420-R-12-004, August 2012)

Van Dingenen R, Dentener F J, Raes F, Krol M C, Emberson L and Cofala J 2009 The global impact of ozone on agricultural crop yields under current and future air quality legislation *Atmos. Environ.* **43** 604–18

Wagstrom K M, Pandis S N, Yarwood G, Wilson G M and Morris R E 2008 Development and application of a computationally efficient particulate matter apportionment algorithm in a three-dimensional chemical transport model *Atmos. Environ.* **42** 5650–9

Washington State Department of Commerce Carbon Tax Assessment Model (http://commerce.wa.gov/growing-the-economy/energy/washington-state-energy-office/carbon-tax/)

We Are Still In Who's (https://wearestillin.com/signatories)

Wilkinson P *et al* 2009 Public health benefits of strategies to reduce greenhouse-gas emissions: household energy *Lancet* **374** 1917–29

Wittig V E, Ainsworth E A and Long S P 2007 To what extent do current and projected increases in surface ozone affect photosynthesis and stomatal conductance of trees? A meta-analytic review of the last 3 decades of experiments *Plant, Cell Environ.* **30** 1150–62

Zanobetti A, Franklin M, Koutrakis P and Schwartz J 2009 Fine particulate air pollution and its components in association with cause-specific emergency admissions *Environ. Health* **8** 1860

Zanobetti A and Schwartz J 2009 The effect of fine and coarse particulate air pollution on mortality: a national analysis *Environ. Health Perspect.* **117** 898–903