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Quantifying the health impacts of eliminating air pollution emissions in the City of Boston

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Abstract

Cities around the world are taking action to limit greenhouse gas emissions through ambitious climate targets and climate action plans. These strategies are likely to simultaneously improve local air quality, leading to public health and monetary co-benefits. We quantify and monetarily value the health impacts of eliminating emissions from the City of Boston, and in doing so, highlight the importance of considering health impacts alongside environmental impacts of local climate action. We simulated at a 4 km resolution how the elimination of anthropogenic emissions from the City of Boston would impact air quality within a 120 km by 120 km study domain. We then estimated how this change in air quality would impact a number of annual health outcomes, as well as the associated monetary savings. We found that eliminating anthropogenic emissions from Boston would result in a decline in PM_{2.5} concentration across the entire study region ranging from 8.5 $\mu\text{g m}^{-3}$ in Boston to less than 1 $\mu\text{g m}^{-3}$ elsewhere in the domain. In addition, we estimate that summer ozone would increase for the Greater Boston Area and areas west, and decrease elsewhere. The monetary impact of the change in air quality on health is estimated to be a \$2.4 billion per year savings across the full domain and \$1.7 billion within Suffolk County only, about 1.4% of the gross domestic product of the county. These monetary impacts are driven primarily by reduced incidence of mortality. We estimate that 288 deaths would be avoided per year across the study domain from eliminating Boston anthropogenic emissions, about six deaths avoided, annually, per 100 000 people. Within Suffolk County, we estimate that 47 deaths would be avoided per 100 000 people, around 16% of all-cause premature mortality. We also found a net decrease in cardiovascular and respiratory illness. Across the study domain, these health benefits would be disproportionately conferred upon people of color.

1. Introduction

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) is plain in its conclusion regarding anthropogenic emissions: 'human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history' (IPCC 2019). Motivated by the global scientific consensus established by the IPCC, political institutions are embracing ambitious targets and climate action plans aimed at abating greenhouse gas emissions (GHG), and carbon dioxide in particular. Climate action plans were initially the domain of nations party to the Kyoto climate

agreement. Increasingly, sub-national governments are embracing complementary and, in some cases, more ambitious GHG emissions targets than their national counterparts. Cities are a crucial piece of the puzzle, as they account for around 70% of global GHG emissions (Seto *et al* 2014). Fortunately, city leaders are leading the way on climate action (Rosenzweig *et al* 2010). The climate leadership group of large global cities, C40, estimated that 228 cities across the globe, representing over 400 million people, have established GHG emissions inventories and targets (ARUP 2014).

While climate targets historically have focused on GHG mitigation, many of the strategies employed

by local governments to address climate change are also effective in the effort to reduce exposure to local air pollutants that directly impact health, like ozone (O_3) and fine particulate matter ($PM_{2.5}$) (Bloomberg and Aggarwala 2008). These types of ancillary benefits have been termed ‘co-benefits’ (Haines 2017). Dense urban environments are ideal settings for implementing strategies with co-benefits, in particular because policies that reduce GHG emissions in urban environments tend to do so by reducing fossil fuel combustion, which in turn impacts local air pollutant emissions (Kinney 2008). For example, urban public and alternative transportation options, such as heavy and light rail, bus rapid transit, bicycling infrastructure, electric scooters, and improved pedestrian access, present an opportunity to reduce personal vehicle use and fossil fuel consumption. Similarly, improvements in the urban buildings sector can reduce energy consumption through energy efficiency retrofits, installation of photovoltaic cells, smaller home footprints, and the use of sustainable building materials for new construction (Younger *et al* 2008). While we focus on the public health co-benefits from local air pollutants here, it is worth noting that GHG emissions reduction strategies are likely to have additional co-benefits outside of this scope (e.g. reduced congestion and improved travel time savings from strategies that shift transportation mode share from single-occupancy vehicles to more efficient modes). Meta-analyses (Liu *et al* 2019) and cohort studies (Laden *et al* 2006, Krewski *et al* 2009) have established strong positive associations between $PM_{2.5}$ and mortality, incidence of heart attacks (Zanobetti and Schwartz 2006), respiratory and cardiac hospital admissions (Zanobetti *et al* 2009), asthma exacerbation (Mar *et al* 2004), lost work days (Ostro 1987), and restricted activity days (Ostro and Rothschild 1989). Similarly, O_3 is positively associated with higher mortality (Levy *et al* 2005), respiratory hospital admissions (Schwartz 1995, Burnett *et al* 2001), lost school days (Chen *et al* 2000), and restricted activity days (Ostro and Rothschild 1989).

Health impact assessments (HIAs) are a useful tool for evaluating the health impacts of public policies and plans particularly before implementation (CDC 2017). They have been used to evaluate hypothetical public policies (Grabow *et al* 2012), conduct economic valuations of environmental impacts through cost of environmental degradation studies (OECD 2014), and to assess the impacts of regulatory actions, like the Clean Power Plan in 2015 (US EPA 2015). Researchers have also paired HIAs with air quality modeling data to estimate the health impacts of air pollution associated with power plants (Buonocore *et al* 2014), traffic congestion (Levy *et al* 2010), and wildfires (Fann *et al* 2018). There is a more limited body of research that examines the health impacts of emissions abatement strategies at the local level, although exceptions exist in Sydney

(Broome *et al* 2015), New York City (Kheirbek *et al* 2016), Guangzhou (Ding *et al* 2016), and a few other cities. The health impacts of city-level policies, and particularly climate action plans including similar policies to those mentioned above, is a relatively understudied area, despite the relative importance of urban policies to climate and health outcomes.

In the interest of demonstrating the potential of city climate action plans to provide co-benefits to health, we model how the City of Boston’s climate action plan might impact health by eliminating emissions. The City of Boston was an attractive case to study for several reasons. It recently adopted one of the nation’s most ambitious climate action targets: in 2016, Mayor Walsh pledged to achieve carbon neutrality by 2050. In support of the Boston Green Ribbon Commission and to inform the City’s climate actions, Boston University’s Institute for Sustainable Energy has already modeled strategies across four sectors to meet the Mayor’s target: buildings, transportation, waste, and energy (Boston Green Ribbon Commission 2019). These strategies, while focused on GHG emissions reductions, are likely to achieve significant health co-benefits through reduced air pollution; however, analyses to-date had not quantified those benefits. By focusing the present analysis on the impacts of eliminating emissions in Boston, there is a unique opportunity to inform the discourse around implementation of Boston’s climate action plan.

In the present study, we carried out an initial bounding analysis to estimate how completely eliminating anthropogenic emissions in the City of Boston would change air quality ($PM_{2.5}$ and O_3) across Eastern Massachusetts. Our analysis approximates one scenario that may be achieved through the Carbon Free Boston plan, though the city may also achieve carbon neutrality without entirely eliminating emissions. After estimating the air quality impacts of eliminating anthropogenic emissions, we quantify the health impacts and health-related monetary savings for mortality and a number of non-fatal health outcomes through a health impact assessment, both within Suffolk County, and in the larger modeling domain. We explore how these impacts are distributed spatially, as well as by race and ethnicity. The study makes three substantive contributions. Firstly, our analysis serves as a best approximation of the benefits incurred should Boston eliminate anthropogenic emissions. Secondly, by estimating the benefits of eliminating anthropogenic emissions, we also quantify the current burden of mortality and disease due to the status quo emission level. This establishes the baseline level of health burden due to anthropogenic emissions that climate action plans like Carbon Free Boston will reduce. Finally, in estimating the distribution of mortality benefits by race and ethnicity adjusted for population, we demonstrate the potential for urban climate action plans to disproportionately benefit

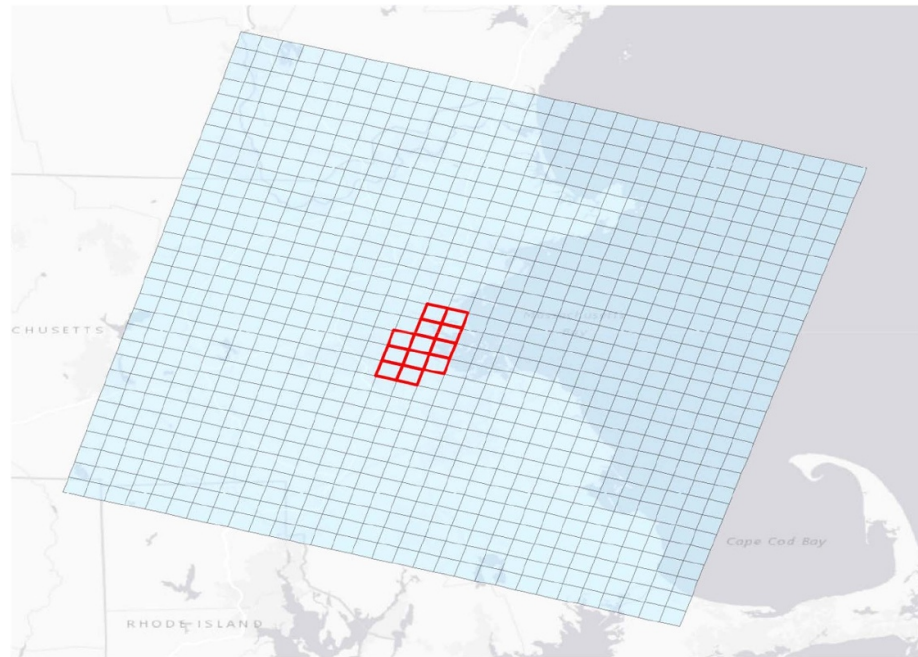


Figure 1. 120 km \times 120 km CMAQ study domain. Grid squares outlined in red are those over the City of Boston where anthropogenic emissions were set to zero in the zero emissions scenario, approximating the impact of the Carbon Free Boston plan.

communities of color who have suffered historical environmental injustice. Broadly, this study provides further insight into the health benefits of city-level climate action, as well as highlights the importance of considering health impacts in the evaluation of urban policies.

2. Methods

2.1. Estimating change in air quality

To estimate how air quality would change if the City of Boston eliminated anthropogenic emissions, we devised two model scenarios for Eastern Massachusetts. In the first scenario, ‘the base case,’ we modeled current air quality across the region to reflect the status quo. In the second scenario, ‘the zero emissions case,’ we used the same model to estimate how air quality across the region would change if the City of Boston eliminated all anthropogenic emissions. The difference in air quality between the two scenarios reflects our estimate of how eliminating emissions sourced from the City of Boston would affect air quality across Eastern Massachusetts compared to current conditions. While emissions controls will likely continue to improve air quality over the next 50 years, climate change is expected to exacerbate pollutant concentrations (Tagaris *et al* 2007, Jacob and Winner 2009). Other demographic changes will also occur, including population growth, potentially increasing emissions, and changing exposures. Given the uncertainties involved in forecasting the various factors, here, we opted to compare the zero emissions case to the more certain current case.

To estimate air quality in the two scenarios, we used the Community Multiscale Air Quality (CMAQ) model (US EPA Office of Research and Development 2017) to model ambient $\text{PM}_{2.5}$ and O_3 . We applied the CMAQ model, using multiple nests (36 km resolution nationally, 12 km over the eastern U.S., and 4 km over an inner modeling domain). The inner domain was 120 \times 120 km centered on the City of Boston and spans Eastern Massachusetts, capturing portions of the surrounding states (figure 1). While Boston makes up only a small portion of the domain, its emissions impact the entire region. We performed model simulations for the entire year of 2011 (the most recent year available that met our needs) to estimate hourly concentrations for both pollutants for each 4 km grid square. The meteorology for CMAQ is from the Weather Research Forecasting (WRF) Model (Skamarock *et al* 2008). Meteorological inputs to WRF consisted of North American Mesoscale Forecast System (NAM) analysis data, along with National Centers for Environmental Prediction (NCEP) Automated Data Processing (ADP) surface and upper air observational data to nudge model results toward observations. WRF inputs were then processed by the Meteorology-Chemistry Interface Processor (MCIP) for use in the air quality model. For the base case scenario, emissions for CMAQ are from the US EPA 2011 National Emissions Inventory (NEI) Emissions Modeling Platform. A detailed description of this NEI platform is given by US EPA (2016). In brief, the NEI platform provides emissions from several source groups at either the county or the individual facility level depending on the type of source. The emissions

Table 1. Anthropogenic emissions and sources zeroed out for the City of Boston. Check mark indicates that emissions of the pollutant from the specified source category were included in the base case simulations and zeroed out for the zero emissions case.

Source Category	CO	NH ₃	NO _x	PM ₁₀	PM _{2.5}	SO ₂	VOC
Fugitive Dust	—	—	—	✓	✓	—	—
Agriculture ^a	—	—	—	—	—	—	—
Commercial Marine Sources	✓	✓	✓	✓	✓	✓	✓
Miscellaneous Area Sources	✓	✓	✓	✓	✓	✓	✓
Offroad Mobile	✓	✓	✓	✓	✓	✓	✓
Onroad Mobile	✓	✓	✓	✓	✓	✓	✓
Oil & Gas	✓	✓	✓	✓	✓	✓	✓
Electric Generating Units	✓	✓	✓	✓	✓	✓	✓
Fires ^a	—	—	—	—	—	—	—
Other Industrial Point Sources	✓	✓	✓	✓	✓	✓	✓
Rail	✓	✓	✓	✓	✓	✓	✓
Residential Wood Combustion	✓	✓	✓	✓	✓	✓	✓

^aNo sources of agriculture or fire emissions were located in the City of Boston.

are allocated temporally and spatially onto the modeling grid using the Sparse Matrix Operator Kernel Emissions (SMOKE) Modeling System (Baek and Seppanen 2018).

For the zero emissions scenario, we used the same model inputs as the base case scenario except that we set anthropogenic emissions to zero for the 12 4 km grid squares containing the City of Boston. We define anthropogenic emissions broadly in this work. Table 1 provides a summary of the sources and pollutants that are treated as anthropogenic emissions in the analysis. After the City of Boston anthropogenic emissions are zeroed out, the only emissions remaining for those model grid cells are from biogenics (i.e. vegetation and soil), lightning NO_x, wildfires, soil crustal matter from CMAQ's windblown dust emissions module, and sea salt (for grid cells containing salt water). Though anthropogenic GHG emissions would also be reduced in this scenario, we do not consider any changes in GHG concentrations or related effects such as radiative forcing.

2.2. Estimating health impacts and their monetary value

Based on the CMAQ model outputs, we used the USEPA Environmental Benefits Mapping and Analysis Program (BenMAP) Community Edition v1.5 to estimate how the changes in PM_{2.5} and O₃ air quality would affect associated health outcomes. The CMAQ model output was used to calculate the daily average PM_{2.5} and maximum daily 8-hour average O₃ concentrations for each day of the model year. We ingested these files into R Studio v1.2 (R v. 3.6.1) and reformatted them according to the input specifications of BenMAP, maintaining the daily concentration estimates for each pollutant. We then calculated the change in PM_{2.5} and O₃ concentrations for each of the 900 4 km grid squares between the base case scenario and the zero emissions scenario using BenMAP. This approach enabled BenMAP to calculate the appropriate temporal aggregation of the exposure data for a given health impact function. For PM_{2.5},

we used annual average; for O₃, we estimated health impacts for the warm season only (April 1 to September 30).

We then estimated how the change in air quality from the elimination of City of Boston emissions would impact health outcomes for each 4 km grid square in the study domain using concentration-response functions approved by USEPA for rule-making and provided in BenMAP, which relate a change in pollutant concentration to change in the incidence of a health endpoint. Recognizing the sensitivity of our findings to PM_{2.5}-related mortality in particular, we calculated a high estimate using the concentration-response function found in Laden (Laden *et al* 2006) and low estimate based on the more conservative relationship found in Krewski (Krewski *et al* 2009). Using BenMAP-supplied 2010 U.S. Census population and endpoint-specific baseline incidence or prevalence data, we then aggregated to the county-level, paying close attention to Suffolk County as an estimate of the benefits conferred upon the City of Boston by its own climate action (Boston accounts for 87% of the population of Suffolk County). For mortality, where BenMAP offers the user a choice of baseline incidence, we used the most recent available race-stratified data from CDC WONDER for years 2007–2016. It should be noted that there would be health impacts outside of the inner, fine domain, so the actual impacts are likely larger than those calculated here.

Finally, we estimated the monetary value of all endpoints using the valuation functions included in BenMAP. The estimated change in incidence of health outcomes provided the input for the valuation functions. We used the valuation function that matched the concentration-response function employed (e.g. work days lost due to PM_{2.5} pollution were valued using a lost-wages valuation function). We estimated monetary valuation impacts at the county level in 2015 U.S. dollars. As we were able to calculate monetary savings for all health endpoints across both pollutants, we sum valuation

Table 2. Population characteristics for the study domain and sub-domain, Suffolk County, MA, from BenMAP model.

	Full Domain		Suffolk County, MA Only	
	Population	Proportion	Population	Proportion
Non-Hispanic White	5 762 519	79.1%	367 184	50.9%
Hispanic	674 194	9.3%	143 455	19.9%
Non-Hispanic Black	435 391	6.0%	147 359	20.4%
Non-Hispanic Asian	396 563	5.4%	62 368	8.6%
Non-Hispanic Native American	15 578	0.2%	1657	0.2%
<i>Total Population</i>	7 284 245	100%	722 023	100%

results and present the net monetary savings for both pollutants.

2.3. Distribution of impacts by race and ethnicity

To evaluate how eliminating anthropogenic emissions affected health disparities by race and ethnicity, we estimate change in mortality incidence for five race and ethnicity categories using county-level race-stratified baseline incidence of mortality. To calculate net population-adjusted deaths avoided, we first estimated mortality benefits by race and ethnicity separately for PM_{2.5} and O₃ and then summed the two population-adjusted rates. This approach was necessary because the health impact functions used for PM_{2.5} mortality and O₃ mortality did not perfectly align with regard to age groups, resulting in slightly different study populations.

2.4. Grid definition to allocate population

BenMAP conducts health impacts analysis at whatever the resolution of the air quality data (in this case, 4 km) and then aggregates health impacts to the user's preference for meaningful analysis. Given that our baseline incidence data for health impacts is at the county-level resolution, we aggregate our health impact results to the county level. As BenMAP's area-weighted algorithm does not account for population density, and can result in less precise allocation of population when a grid square overlaps a county boundary, we intersected the BenMAP county border shapefile with a 4 km CMAQ grid fishnet in ArcMap 10.6 to create a grid definition that broke these overlapping cases into multiple cells, or 'shards.' We then used R Studio 1.2 (R v. 3.6.1) to assign the original air quality impacts modeled at the 4 km level to all of the shards within each 4 km grid square. Using this revised grid definition, BenMAP did not need to apply its area-weighting algorithm when aggregating results.

3. Results

3.1. Population characteristics of the study domain

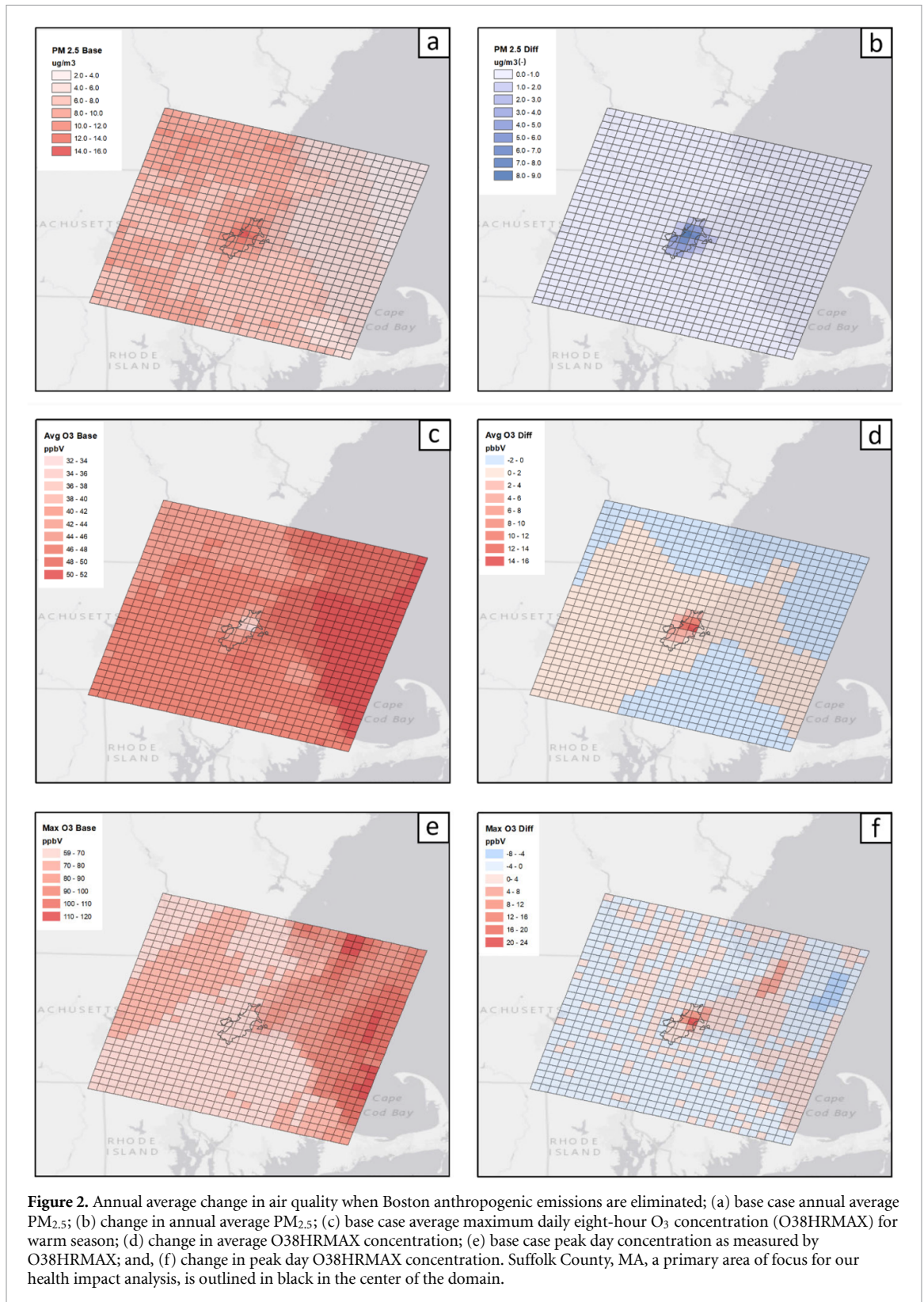
Approximately 7.3 million people live in the study region, with race and ethnicity distributed as noted in table 2. Suffolk County is of particular interest for our analysis because most of the air quality and health benefits are likely to be conferred there and because it

is a good proxy for the City of Boston. Suffolk County is more diverse by race and ethnicity than the full study domain. Around 722 000 people live in Suffolk and it is just barely majority non-Hispanic White, with both Hispanic and non-Hispanic Black populations each accounting for 20% of county population. These data presented are from our BenMAP model output and match data from the 2010 U.S. Census population data, as expected.

3.2. Change in air quality

Based on CMAQ model results, we find that when City of Boston anthropogenic emissions are eliminated, annual average PM_{2.5} concentrations would decrease for most of the 4 km cells in the study domain; however, the vast majority of the region (97.5%) would see a relatively small (<1 $\mu\text{g m}^{-3}$) decrease in PM_{2.5} compared to the Greater Boston Area (see figure 2(b)). The City of Boston, as defined by the zone outlined in figure 1, on average would see a decrease in PM_{2.5} concentration of 5.0 $\mu\text{g m}^{-3}$. The maximum decrease in PM_{2.5} concentration would occur over downtown Boston, where ambient PM_{2.5} would decrease from 15.8 $\mu\text{g m}^{-3}$ in the base case scenario to 7.3 $\mu\text{g m}^{-3}$ in the zero-emissions scenario.

Eliminating anthropogenic emissions from the City of Boston has a more complex effect on O₃ concentrations across the model domain than PM_{2.5}. Some of the grid squares would see an increase in average O₃ concentration, and some a decrease due to the relationship between O₃ and NO_x. In high NO_x environments, the reaction of NO with O₃ to produce NO₂ and O₂ can be a sink for O₃ as NO₂ acts to scavenge the hydroxyl radical. In the zero emissions scenario, decreased NO_x likely leads to higher O₃ concentrations in those high NO_x areas, albeit with reductions in O₃ downwind. We estimate that O₃ daily eight-hour average concentrations during the warm season would increase in the City of Boston and areas west (figure 2(d)). A 30 km by 20 km sub-region of the modeling domain would see at least a 1 ppb increase in O₃ concentration, with a maximum increase of 14.2 ppb in the area over Boston's Logan Airport. About half of the modeling domain (45%) would see a small decrease in annual daily eight-hour average O₃ concentrations of less than 1 ppb.



While we did not use peak day O_3 concentration change for our health impact assessment, we share these results here for additional context (see figure 2(f)). Eliminating emissions from the City of Boston would increase peak day O_3 concentrations in the Boston area and northeast of the city and decrease concentrations elsewhere in the modeling domain, particularly the area north of Cape Cod.

The greatest increase in peak day O_3 would also occur in downtown Boston, where modeled peak day O_3 would increase from 59 ppb to 80 ppb, in the absence of any further emissions reduction by upwind cities. The greatest decrease in peak day O_3 of 4.5 ppb would occur offshore from 107.9 ppb to 103.4 ppb.

The CMAQ model results were compared against observations from the Air Quality System (AQS)

Table 3. Statistical evaluation for MDA8 O₃ (N = 2895) and daily average PM_{2.5} (N = 4140).

	NMB(%)	NME (%)	FB (%)	FE (%)	R
MDA8 O ₃ Performance	7.6	20.4	n/a	n/a	0.62
MDA8 O ₃ Criteria	<±15	<25	n/a	n/a	>0.50
PM _{2.5} Performance	29.5	59.8	15.2	47.6	0.58
PM _{2.5} Criteria	<±30	<50	<±60	<75	>0.40

Table 4. Health and monetary impacts from change in PM_{2.5} when anthropogenic emissions from the City of Boston are eliminated. Confidence internals in parentheses.

Endpoint	Full Domain		Suffolk County, MA Only	
	Incidence Avoided	Monetary Savings (\$2015 millions)	Incidence Avoided	Monetary Savings (\$2015 millions)
Mortality (low estimate)	125 (85, 164)	998 (92.7, 2710)	93 (63, 123)	746 (69.4, 2030)
Mortality (high estimate)	316 (144, 482)	2530 (218, 7270)	236 (108, 358)	1890 (163, 5410)
Non-fatal Acute Myocardial Infraction	116 (30, 192)	9.63 (2.48, 16.0)	77 (20, 127)	6.43 (1.69, 10.5)
Asthma, Emergency Room Visits	173 (46, 296)	0.07 (0.02, 0.11)	146 (39, 248)	0.056 (0.015, 0.096)
Cardiovascular Hospital Admissions	46 (25, 66)	1.77 (0.98, 2.55)	33 (19, 48)	1.29 (0.72, 1.86)
Respiratory Hospital Admissions	35 (20, 50)	1.03 (0.59, 1.46)	25 (15, 35)	0.73 (0.42, 1.04)
Chronic Bronchitis	117 (3, 224)	24.4 (0.64, 46.8)	87 (2, 165)	18.1 (0.48, 34.5)
Minor Restricted Activity Days	154 000 (126 000, 181 000)	9.83 (5.17, 14.9)	120 000 (98 000, 141 000)	7.66 (4.03, 11.6)
Work Days Lost	26 500 (22 400, 30 400)	5.05 (4.28, 5.80)	20 800 (17 600, 23 900)	3.82 (3.24, 4.39)
Asthma Exacerbation	23 600 (−31 200, 70 500)	4.67 (−6.17, 13.9)	17 100 (−23 200, 50 300)	3.39 (−4.57, 9.95)

Table 5. Health and monetary impacts from change in O₃ when anthropogenic emissions from the City of Boston are eliminated. Confidence internals in parentheses.

Endpoint	Full Domain		Suffolk County, MA Only	
	Incidence Avoided	Economic Savings (\$2015 millions)	Incidence Avoided	Economic Savings (\$2015 millions)
Mortality	−28 (−36, −19)	−221 (−600, −20.6)	−23 (−31, −16)	−187 (−506, −17.4)
Youth Asthma Exacerbation	−6290 (−45 700, 31 100)	−1.25 (−9.01, 6.13)	−5190 (−37 800, 25 600)	−1.03 (−7.45, 5.04)
School Loss Days	−13 500 (−22 000, −5130)	−1.30 (−2.10, −0.49)	−11 000 (−18 000, −4200)	−1.07 (−1.73, −0.40)
Emergency Room Visits, Asthma	−320 (−586, −73)	−0.12 (−0.23, −0.03)	−291 (−534, −66)	−0.11 (−0.21, 0.03)
Respiratory Hospital Admissions	−55 (−104, −9)	−1.31 (−2.52, −0.12)	−47 (−87, −8)	−1.09 (−2.09, −0.10)
Minor Restricted Activity Days	−61 600 (−98 300, −25 200)	−3.94 (−7.31, −1.45)	−52 900 (−84 500, −21 600)	−3.38 (−6.28, −1.25)

database which contains data from EPA, state, and tribal air quality monitoring stations. The results of the statistical analysis for the maximum daily average 8-hour ozone (MDA8 O₃) and daily average PM_{2.5} concentrations are provided (table 3). Summary results are provided for normalized mean bias (NMB), normalized mean error (NME), and Pearson correlation coefficient (r). For PM_{2.5}, fractional bias (FB) and fractional error (FE) are also provided. Performance for MDA8 O₃ consistently meets or exceeds recent

performance criteria (Emery *et al* 2017), though with a slight high bias, except at high concentrations. Performance for daily mean PM_{2.5} also meets or exceeds most recent criteria goals (Boylan and Russell 2006, Emery *et al* 2017), with concentrations biased high on average.

3.3. Health impacts and their valuation

We present the health impacts and monetary savings from the change in PM_{2.5} and O₃ concentrations

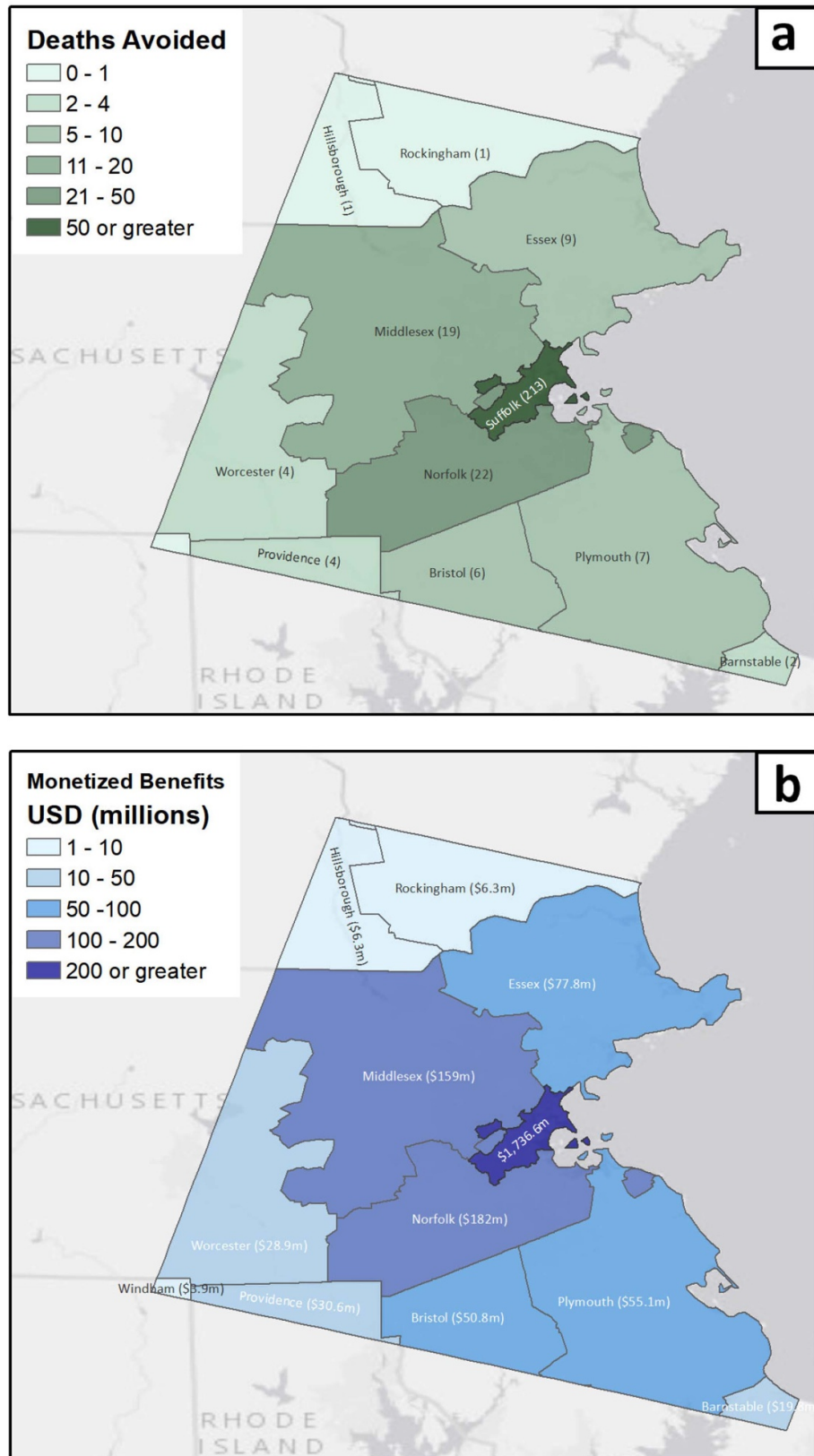


Figure 3. Spatial distribution of health impacts and their valuation by county for study domain; (a) distribution of net deaths avoided by county for PM_{2.5} and O₃ due to elimination of Boston anthropogenic emissions; (b) distribution of net monetary savings (\$2015 millions) by county from health impacts.

from the elimination of anthropogenic emissions in the City of Boston in tables 4 and 5. We provide these results both for the full domain and for Suffolk County, MA. Across the full domain, we find that

lower PM_{2.5} levels would result in a high-estimate of 316 (95% CI: 144, 482) and a low-estimate of 125 (95% CI: 85, 164) deaths avoided annually. We also estimate that reduced PM_{2.5} would result in 116 (95%

Table 6. Population-adjusted deaths avoided due to air quality changes by ethnicity and race.

	PM _{2.5} Deaths Avoided	PM _{2.5} Deaths Avoided per 100 000	O ₃ Deaths Avoided	O ₃ Deaths Avoided per 100 000	Net Deaths Avoided per 100 000
Non-Hispanic Black	46	17.6	−4.5	−1.0	16.6
Non-Hispanic Asian	20	7.9	−1.9	−0.5	7.4
Hispanic	25	6.9	−2.5	−0.4	6.5
Non-Hispanic Nat. American	1	7.6	0	−0.3	7.3
Non-Hispanic White	225	5.5	−19	−0.3	5.2
All	316	6.4	−28	−0.4	6.0

CI: 30, 192) fewer non-fatal heart attacks; 173 (95% CI: 46, 296) fewer asthma-related emergency room visits; 46 (95% CI: 25, 66) fewer hospital admissions due to cardiovascular complications not including acute myocardial infarction, 35 (95% CI: 20, 50) fewer hospitalizations due to respiratory illness across the full domain. In addition, we estimate 26 500 (95% CI: 22 400, 30 400) fewer workdays lost and 154 000 (95% CI: 126 000, 181 000) fewer restricted activity days when individuals restrict daily activities due to air pollution but do not miss work. For these outcomes, the share of full domain benefits conferred upon Suffolk County range from 66% to 84%; with around three-quarters of the lives saved occurring in Suffolk County.

The health impacts associated with increased O₃ concentration are considerably smaller than those associated with PM_{2.5}, though they are negative, indicating an *increase* in incidence. Across the full domain, we estimate that 28 (95% CI: 19, 36) more deaths would occur due to increased O₃ during the warm season. We find that there would be 320 (95% CI: 73, 586) more emergency room visits due to asthma and 55 (95% CI: 9, 104) more hospital admissions due to respiratory illness. We also estimate 13 500 (95% CI: 5130, 21 900) more school days lost and 61 600 (95% CI: 22 200, 98 300) more restricted activity days in the full domain. As with PM_{2.5} the health impact associated with O₃ are concentrated in Suffolk County, which is estimated to receive between 82% and 91% of full domain health impacts, depending on the endpoint. Full results are presented in table 5.

For the full domain, we estimate that net mortality incidence from PM_{2.5} and O₃ would decrease by 288 deaths per year should Boston eliminate anthropogenic emissions. Cumulative net monetary savings for the full domain would be \$2.4 billion annually, with Suffolk County receiving 74% of full domain monetary savings from reduced mortality and morbidity, or \$1.7 billion per year.

3.4. Distribution of mortality incidence

We demonstrate the distribution of health impacts by geography, race, and ethnicity with net mortality incidence, as it is a common endpoint for both pollutants. While the majority of net deaths avoided

(213 per annum; 68%) is conferred upon Suffolk County, counties bordering Suffolk that constitute the Greater Boston Area also see substantial mortality benefits (9–22 net deaths avoided per annum). Marginal reductions in mortality extend across the entire study region including into New Hampshire, Rhode Island, and Connecticut (figure 3(a)). Net deaths avoided per 100 000 people is estimated to be six for the full study domain and 47 for Suffolk County. We also estimated net annual monetary savings from all health impacts for both pollutants by county using our high mortality estimate (figure 3(b)).

After adjusting for population size, we estimate that the non-Hispanic Black population would see three-times the net deaths avoided compared to the non-Hispanic White population across the full study domain (see table 6); about 17 vs. five deaths avoided per 100 000 people. Population-adjusted deaths avoided amongst Hispanic and non-Hispanic Asian groups are also disproportionately higher than the reference group, non-Hispanic White.

4. Discussion

Our results suggest that eliminating anthropogenic emissions from the City of Boston would have substantial health and monetary benefits across the study region, highlighting the potential for local climate policies to deliver public health and monetary co-benefits alongside intended climate objectives. We estimated 288 net deaths would be avoided per year across the study domain; six deaths avoided per 100 000 people. Put in context, motor vehicle crashes in Massachusetts killed 6.3 people per 100 000 in 2016 (Massachusetts Department of Public Health 2018). It is also clear that those taking action to reduce emissions, namely the people of Boston, would benefit the most from the implementation of the City of Boston's climate action plan. We estimate that the annual reduction in population-adjusted mortality for Suffolk County (of which Boston constitutes 87% by population) would be about 47 per 100 000 people, around 16% of all-cause premature mortality in the county in 2016 (301.1 per 100 000). Improvements in non-fatal health outcomes follow a similar spatial pattern of distribution.

The estimated monetary benefits incurred through improved health outcomes are also of notable magnitude. Suffolk County, driven by the City of Boston, is an economic powerhouse in New England, generating an estimated \$120 billion in gross domestic product in 2018 (2015 U.S. dollars) according to the U.S. Bureau of Economic Analysis. The \$1.7 billion in annual monetary benefits to Suffolk County, MA is equivalent to approximately 1.4% of the gross domestic product of Suffolk County. While the climate action plan studied is limited to Boston, its impacts would be felt statewide. The estimated \$2.4 billion in monetary benefits across the entire study region amounts to about 0.4% of the \$568 billion GDP of the state of Massachusetts.

As 79% of the population of the region is non-Hispanic White, it is to be expected that most of the deaths avoided would be conferred upon that population. After adjusting for population size, however, we estimated that the non-Hispanic Black population would benefit at three times the rate of the non-Hispanic White population across the full domain. This disparity is due to a combination of the relative diversity of the Greater Boston Area compared to the rest of the study region, air quality changes concentrated in the Greater Boston Area, and differing baseline incidence of mortality by race. It is also clear that the adverse health outcomes associated with the current distribution of air pollutants is born disproportionately by minorities. Thus, climate action plans like Carbon Free Boston may help to address historical and current environmental injustice affecting urban minority communities.

The health impacts estimated in this study are driven by the changes in $PM_{2.5}$ and O_3 concentrations modeled in CMAQ that result from eliminating emissions from the City of Boston. Notably, while $PM_{2.5}$ concentrations declined substantially in the Greater Boston Area, O_3 concentrations increased in the same area. As noted above, this is likely due to the relationship between NO_x and O_3 in high NO_x environments. The inverse relationship between $PM_{2.5}$ and O_3 is consistent with similar studies. For example, Grabow *et al* (2012) estimated that eliminating short distance car trips across 11 urban areas in the Midwest would decrease $PM_{2.5}$ and increase O_3 during the warm season in urban areas (Grabow *et al* 2012). If there are continued NO_x emissions reductions in the Boston region between now and 2050, as is expected, then the NO_x emission reductions disbenefits would decrease, and may even shift to benefits. Further, if upwind cities, like Cambridge, New York, Philadelphia and Providence, also adopted similar climate plans, actions undertaken by the City of Boston would be enhanced as O_3 production in the region would become NO_x -limited.

Our health impact results are relatively consistent with the existing literature studying the effects of abating emissions on health outcomes

in urban environments. Our estimated baseline level $PM_{2.5}$ concentrations over Boston are around twice the 2007 levels in Sydney, Australia modeled by Broome *et al* (2015), but this is consistent with their observation that Sydney enjoys air pollution levels that are lower than comparable cities (we could not compare O_3 due to the different metrics employed). While health impacts are difficult to compare due to differing baseline incidence, population, and effect estimates, it is notable that Broome *et al*'s estimate of 430 premature deaths attributed to anthropogenic $PM_{2.5}$ and O_3 is within an order of magnitude of our estimate of 288 net deaths avoided from eliminating anthropogenic emissions in Boston. Similarly, Kheirbek *et al* (2016) examined the impacts of eliminating mobile emissions sources in New York City with a similar zeroing out emissions methodology to the one employed here and found baseline $PM_{2.5}$ in the range of $\sim 7\text{--}20 \mu\text{g m}^{-3}$ for mobile sources alone and found a corresponding reduction in mortality from the elimination of emissions of 260 deaths per year.

We believe our analysis represents the current best estimate of the air pollution-related health impacts from the City of Boston's climate action plan. That said, this analysis is not meant to be a prediction of future policy impacts compared to a robust modeled business as usual case, but rather a bounding analysis to estimate the magnitude of health impacts compared to today's conditions. By modeling the change in air quality resulting from eliminating anthropogenic emissions, we analyze a possible future scenario that could be achieved through the policies and programs laid out in the plan; however, our analysis has some limitations.

As the objective of the Carbon Free Boston plan is to achieve carbon-neutrality, not the elimination of all emissions, it is likely that there would be some residual emissions from the City of Boston that would be offset through the purchase of carbon credits. We do not model this residual in our analysis. In addition, we recognize that even strategies that successfully eliminate all carbon emissions may result in some residual anthropogenic emissions depending on the strategies implemented and external factors. Our results are also highly sensitive to the concentration-response functions employed to estimate health impacts. The number of annual net deaths avoided changes by a factor of three when comparing the low point estimate, 97, to the high estimate, 288. Our estimate of net annual economic benefits is subject to a similar range (\$825 million to \$2.4 billion) due to the sensitivity of monetary savings estimates to the magnitude of deaths avoided. By providing two estimates for $PM_{2.5}$ mortality, we aim to address some of the uncertainty due to concentration-response-function choice present in this modeled analysis. In addition, we exclusively selected functions from the list of those approved by the USEPA for rulemaking.

It is notable that even the low-range estimate is large enough to merit consideration by policymakers.

Our results are also sensitive to the assumptions underlying the CMAQ model and its inputs (e.g. emissions), as well as to the model's fidelity to observed monitoring data. The most recent model run that was linked to a National Emissions Inventory-year available for our zero emissions analysis was from the year 2011. As air quality, and the spatial distribution of pollutants, can exhibit temporal variation, the use of a single year for our model also introduces some uncertainty (Garcia-Menendez *et al* 2017, Deser *et al* 2020). The use of a single year for the analysis also means that the specific meteorological conditions of the simulation year influence the air quality results. To provide context for the meteorological conditions of 2011, we can compare the 2011 meteorology of the Northeast Climate Region to the typical conditions. On average, 2011 was the sixth warmest year on record (1.2 °C greater than the 1901–2000 mean) and had the greatest precipitation on record for the Northeast Climate Region (13 inches greater than the 1901–2000 mean) (NOAA 2020). Higher temperatures would tend to increase O₃ concentrations as higher temperatures can increase the rate of chemical reactions. Greater precipitation would tend to decrease both PM_{2.5} and O₃, as more pollutants would be removed from the atmosphere through wet deposition. We can provide an approximation of the importance of meteorology by comparing the 4th highest daily 8-hour average O₃ concentration and the annual mean PM_{2.5} concentration for the Boston-Cambridge-Newton, MA-NH core-based statistical area (CBSA) of our simulation year with the three-year average concentration which smooths out the effects of year-to-year meteorological variability. The 2011 4th highest daily 8-hour average ozone concentration for this CBSA was 73 ppb, while the three-year average was 73.7 ppb. The annual mean PM_{2.5} concentration for this CBSA was 10.3 μg m⁻³, while the three-year average was 10.2 μg m⁻³. Since the yearly and three-year concentrations compare well, we conclude that year-to-year meteorology does not substantially affect the results of the analysis. We do, however, note that this meteorological analysis is limited to mean values and thus does not account for the effects of extreme heat and stagnation which typically co-occur with episodes of elevated O₃ and PM_{2.5} concentrations (Schnell and Prather 2017).

As we only consider the health benefits and monetary savings from changes in PM_{2.5} and O₃ concentrations, our results may be biased downward. It is likely that there are other benefits from eliminating anthropogenic emissions from the City of Boston; for example, from: reducing additional pollutants not evaluated for health impacts here, including air toxics, CO, NO₂, and SO₂; the specific policies implemented (e.g. benefits from increased

physical activity resulting from mode shift away from automobiles); and, non-health related environmental benefits.

Finally, we recognize that it is unlikely that the City of Boston would implement a climate action plan in a vacuum. For example, the neighboring city of Cambridge, MA also has a climate action plan aimed at achieving carbon neutrality by 2050. By studying the impact of a single municipality's climate action plan, however, we align our research with the municipal policymaking process and demonstrate the regional impacts of just the City of Boston's climate actions. We believe that regional analysis also has an important role to play in understanding the cumulative impacts of multiple climate action plans, and is an important topic for future research. It is notable, particularly in the case of ozone, that the actions of the City of Boston are estimated to have considerable impacts on air quality throughout our entire 120 km by 120 km model domain. In fact, impacts are likely to extend beyond the modeling domain. This highlights the potential benefits of concerted action and the special role that larger municipalities play in impacting air quality across a broader region.

5. Conclusion

Our study suggests that the Greater Boston Area would realize substantial health benefits should the City of Boston achieve the ambitious climate policy goals set forth in the Carbon Free Boston plan. We find that the elimination of anthropogenic emissions from the City of Boston would save hundreds of lives per year, reduce incidence of cardiovascular and respiratory illnesses, and achieve annual monetary savings for Suffolk County alone that are on par with 1.4% of the county's gross domestic product. Our results suggest that municipal climate policies have great potential to achieve health co-benefits, and that health impacts merit consideration as a core part of the way climate policies are evaluated by policymakers and the public.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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