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The Public Health Benefits of Reducing Fine Particulate Matter through Conversion to Cleaner Heating Fuels in New York City

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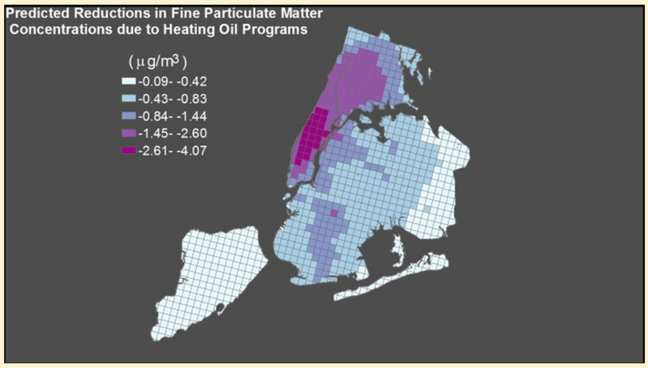
Supporting Information

ABSTRACT: In recent years, both New York State and City issued regulations to reduce emissions from burning heating oil. To assess the benefits of these programs in New York City, where the density of emissions and vulnerable populations vary greatly, we simulated the air quality benefits of scenarios reflecting no action, partial, and complete phase-out of high-sulfur heating fuels using the Community MultiScale Air Quality (CMAQ) model conducted at a high spatial resolution (1 km). We evaluated the premature mortality and morbidity benefits of the scenarios within 42 city neighborhoods and computed benefits by neighborhood poverty status. The complete phase-out scenario reduces annual average fine particulate matter ($PM_{2.5}$) by an estimated 0.71 $\mu g/m^3$ city-wide (average of 1 km estimates, 10−90th percentile: 0.1−1.6 $\mu g/m^3$), avoiding an estimated 290 premature deaths, 180 hospital admissions for respiratory and cardiovascular disease, and 550 emergency department visits for asthma each year. The largest improvements were seen in areas of highest building and population density and the majority of benefits have occurred through the partial phase out of high-sulfur heating fuel already achieved. While emissions reductions were greatest in low-poverty neighborhoods, health benefits are estimated to be greatest in high-poverty neighborhoods due to higher baseline morbidity and mortality rates.



■ INTRODUCTION

Exposures to fine particulate matter ($PM_{2.5}$) in air have been associated with many adverse health outcomes including increased airway inflammation, reduced lung function, and changes in heart rhythm and blood pressure leading to increased risks of hospitalizations, emergency department visits and premature death.[1,2] In New York City (NYC), despite improvements in recent years due to federal, state and local regulations, current concentrations of $PM_{2.5}$ in excess of background levels are associated with over 2000 premature deaths, 4800 emergency department visits for asthma, and 1500 hospitalizations for respiratory and cardiovascular disease each year.[3]

Quantifying the benefits of air quality programs is an important step in evaluating the efficacy of regulations, comparing alternative strategies, and communicating to the public the importance of these often costly efforts. While routinely conducted to inform air quality management[4,5] there has been growing recognition of the importance of applying these methods locally to quantify fine-scale variations in policy benefits and evaluate differences in impacts where within-city exposure and population health gradients exist.[6−9] This has led to advancements in methodologies for predicting exposures at a fine resolution using dispersion or photochemical air quality models.[10−12]

In New York City, the primary types of fuels used to for space and water heating are liquid fuel oils and natural gas.[13] Of the liquid fuels, most small residential and commercial buildings use No. 2 oil.[14] Many larger buildings use No. 6 (residual oil), a cheaper, more polluting and viscous refined crude oil byproduct that requires preheating in large boiler systems or blending with lighter distillates to produce No. 4 oil. No. 2 oil and natural gas produce less air contaminants than No. 6 and No. 4 and reductions in fuel sulfur content reduce emissions of $PM_{2.5}$.[14−17]

As part of region-wide air quality management efforts, in the early 2000s the Northeast states began considering regulations to reduce emissions from home heating oil, a significant emitter of fine particles and their precursors.[18] The northeastern U.S. is

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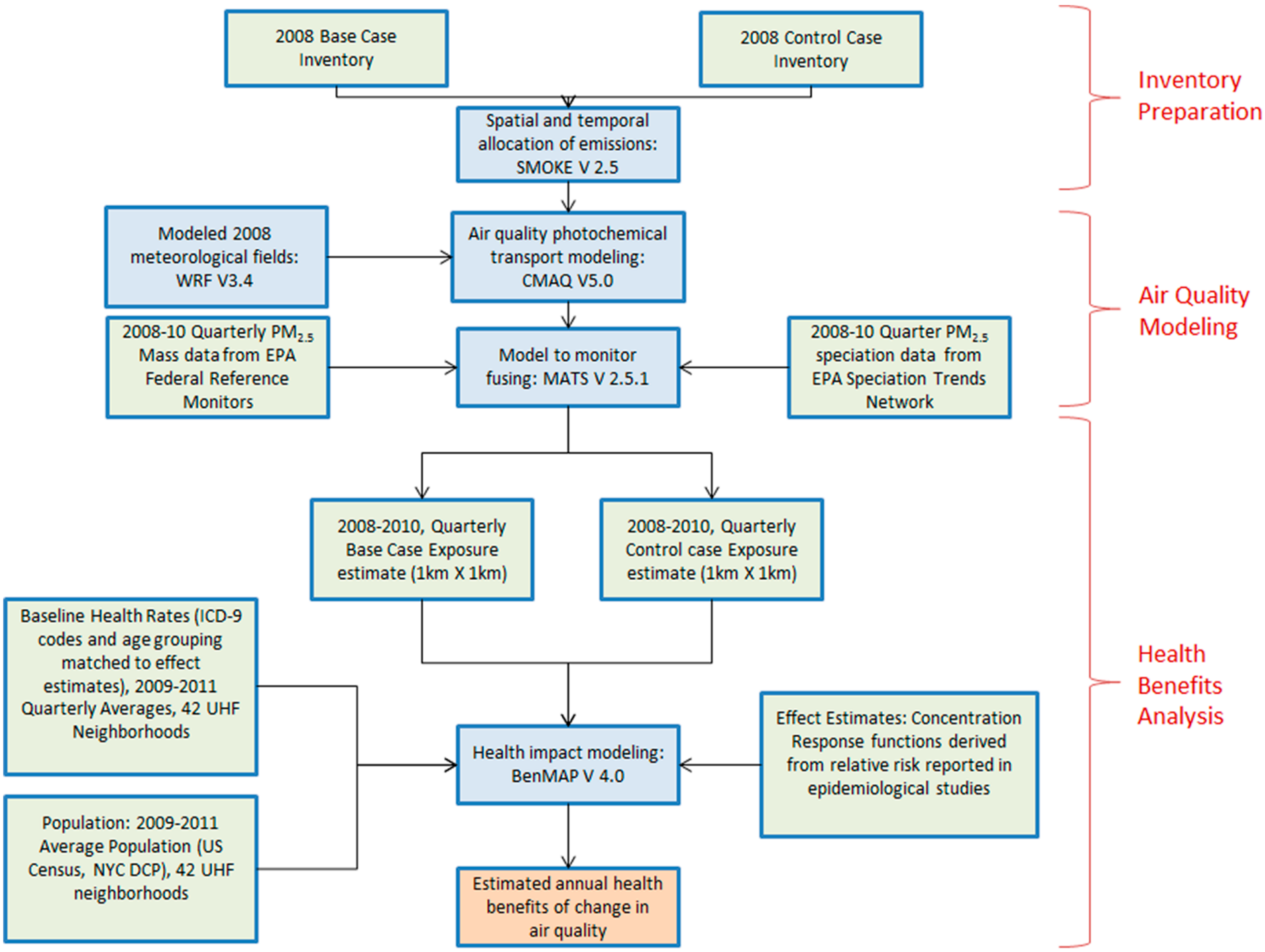

Figure 1. Framework for estimating the $PM_{2.5}$ and associated health benefits of New York fuel oil regulations.

the nation's largest consumer of heating oil, with 32% of NYC housing units using fuel oil in building heating and hot water systems, of which No. 2 distillate oil is the most widely used.[19,20] To control emissions from No. 2 oil, New York State (NYS), supported by advocacy efforts from NYC officials, developed regulations lowering the allowable sulfur content of No. 2 oil from 2000 to 15 ppm (ultralow sulfur heating oil) as of July 2012, resulting in over 95% reduction in SO_2 and $PM_{2.5}$ emissions rates.[14] Between 2012 and 2018, the remaining Northeast states will follow, introducing 15 ppm heating oil on a state by state schedule.

In addition to these regional measures, New York City policy makers set ambitious targets for air quality as part of the City's long-term sustainability plan, PlaNYC.[21] This plan created a unique air quality surveillance program to evaluate neighborhood variation in air pollution,[22] and monitoring results led to a focus on pollutants that stemmed from heating oil. Wintertime monitoring demonstrated that the density of oil burning units was the most important spatial predictor of $PM_{2.5}$ concentrations in NYC, and buildings burning heavier fuel oil distillates—No. 6 oil (residual oil, 3000 ppm allowed sulfur content) and No. 4 oil (blend of distillate and residual oil, 3000 ppm allowed sulfur content)—[23]were associated with higher SO_2 and nickel concentrations.[22,24] Based on these and other studies, NYC began a multiyear strategy in coordination with public and private stakeholders to eliminate the use of No. 4 and No. 6 oil in NYC buildings, issuing regulations in 2011 that will phase out No. 4 and No. 6 heating oil by initially disallowing any permits for No. 6 boilers, effectively requiring all boilers in the city to burn No. 4 oil or cleaner as of 2015. It then requires, by 2030, all boilers in the city use the cleanest available fuels (ultralow sulfur No. 2 oil, natural gas or equivalent).[25] The New York City Council also passed a law to reduce the sulfur limit for No. 4 oil from 3000 to 1500 ppm, and required all heating oils to have 2% biodiesel as of October 2012.[26] To further accelerate conversions to cleaner heating oil, NYC launched the Clean Heat Program with a goal of reducing $PM_{2.5}$ emissions from No. 4 and No. 6 oil use by 50% by 2014.[27] This initiative enlists energy and building professionals to develop relationships and provide no-cost technical assistance to major building owners and property managers and provided financing incentives for boiler conversions. In addition, declining prices have accelerated shifting to natural gas and NYC government is supporting increased distribution of natural gas in underserved areas of the City.

To assess the magnitude and distribution of public health benefits of these emission reduction programs, we developed air quality scenarios reflecting emissions conditions under (1) base conditions, prior to intervention, (2) current-day conditions that account for a partial phase out of high sulfur heating oil in NYC: implementation of the NYS 15 ppm of No. 2 oil requirements, the NYC 1500 ppm of No. 4 oil mandate,

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and partial phase out of No. 6 and No. 4 oil associated with early conversions and Clean Heat Program efforts, and (3) future emissions after complete phase out of all high sulfur fuels. We simulated ambient $PM_{2.5}$ improvements and associated public health benefits of scenarios two and three and examined the distribution of benefits across neighborhoods stratified by poverty. In conducting these analyses, we provide a case-study for the benefits of controlling smaller, widely distributed sources that contribute to fine scale differences in air quality in an urban area with varying population susceptibility. These methods are relevant for evaluating policy in other locations with uncontrolled sources in densely developed areas with large numbers of vulnerable residents.

■ MATERIALS AND METHODS

We followed a modeling framework that included emission inventory development, preparation of meteorological inputs, air quality modeling, combined analysis of air quality modeling and monitoring data (fusing), and $PM_{2.5}$ health benefits analysis (Figure 1).

Emissions Inventory Preparation. We prepared inventories for three nested grids centered over NYC (15-, 5-, and 1 km (km) horizontal resolution) for a base year (prior to regulation) and two scenarios simulating phased implementation of the fuel oil regulations:

2008 Base Case. We used EPA's 2008-based modeling platform derived from the 2008 National Emissions Inventory (NEI).[28] This inventory includes estimates of U.S and Canadian emissions from electric generating units (EGU) and non-EGU point sources, area sources, on-road and nonroad vehicles, wild and prescribed fires, fugitive dust, agricultural sources, commercial marine vessels, and biogenic sources.

To better reflect local conditions, emissions from No. 4 and No. 6 boilers in the non-EGU point and area source inventories were replaced with emissions calculated from local permits. The NYC Department of Environmental Protection (NYCDEP) issues permits on 3 year cycles for all No. 4 and No. 6 boilers which include address and rated annual heat throughput. $PM_{2.5}$, SO_2, NO_x, and CO emissions were calculated for each boiler using rated heat throughput and emissions factors from EPA's AP-42 database.[16] No. 6 oil was assumed to contain 3000 ppm sulfur, consistent with regulations,[23] and No. 4 oil was assumed to constitute a 65%/35% blend of 3000 ppm of No. 6 and 2000 ppm of No. 2 oil based on NYCDEP estimates of local No. 4 content. Emissions were spatially allocated using boiler address.

Similarly, NYCDEP permits all No. 2 boilers with capacity above 350 000 Btu. We replaced No. 2 boiler emissions the non-EGU point and area source inventory with emissions computed from permits, using emission factors for 2000 ppm sulfur No. 2 oil. Emissions from No. 2 boilers below the reporting threshold were estimated by subtracting the emissions from permitted No. 2 boilers from the total No. 2 boilers emissions in the 2008 NEI. These "remainder" emissions were then allocated to grid cells by creating building-specific weights based on interior building area of properties not included in the permit databases[29] and county-specific percent of buildings using No. 2 oil as primary fuel, collected from the 2005–2009 American Community Survey.[30]

Scenario 1 (S1). S1 was prepared to reflect implementation of rules lowering sulfur content of No. 4 and No. 2 oil to 1500 and 15 ppm, respectively, and partial conversions of No. 4 and No. 6 boilers.

NYC's Clean Heat Program tracks the status of Nos. Four and 6 boiler conversions monthly. We reviewed the status as of February 2013 and emissions were adjusted to account for new fuels being used at boilers that had switched or were undergoing switching by applying emissions factors for the new fuel type.[14,16] All No. 4 boilers were reduced using emissions factors for 1,500 ppm of No. 4 oil.

Emissions from all No. 2 boilers above 350 000 Btu were reduced using 15 ppm emissions factors. Emissions in grid cells from No. 2 boilers below 350 000 Btu were adjusted by the ratio of the 2000 and 15 ppm emissions factors, which reduced $PM_{2.5}$ and SO_2 emissions by 98.2% and 99.3% respectively

Scenario 2 (S2). S2 was prepared to estimate emissions upon full implementation of heating fuel regulations in 2030. Emissions from No. 4 and 6 boilers were reduced using emissions factors for ultralow sulfur No. 2 or natural gas, depending on the individual boiler's conversion plan, when available. Where no conversion information was available, the emissions were reduced to equal a natural gas boiler. This assumption provided a conservative estimate of the benefits, due to the higher primary $PM_{2.5}$ emissions factor of natural gas relative to ultralow sulfur oil.[14,16] Emissions from all other sectors remained the same as those in S1.

We used the SMOKE emission processor software (version 3.1) to create air quality modeling inputs for the three scenarios.[31,32] All NYC boilers and NEI point sources were placed in the grid based on their address or using No. 2 oil building weights, while all other sources were allocated to grid cells using EPA spatial surrogate profiles and associated cross reference files.[31]

Air Quality Modeling. Detailed methodological information on meteorological and air quality modeling has been described elsewhere.[33] In short, meteorological fields were developed for four nested grids with 45-, 15-, 5-, and 1-km horizontal resolutions[33] from January first through December 31st 2008 using the Weather Research and Forecasting (WRF) model[34] (the 45 km grid providing boundary conditions for the higher-resolution grids) then processed for CMAQ input using the Meteorology−Chemistry Interface Processor (MCIP).

Simulated $PM_{2.5}$ concentration fields associated with each of the three emissions scenarios were derived by applying CMAQ Version 5.0[35] for 2008. CMAQ simulates the physical and chemical processes of the transport, formation and deposition of $PM_{2.5}$ and predicts hourly concentrations of total $PM_{2.5}$ mass as well as its major constituents in each grid cell. CMAQ has been used extensively for research and regulatory air quality planning and provides a state-of-the-science system for simulating $PM_{2.5}$ levels at the regional and local scale.[36−38]

We evaluated WRF results by comparing patterns of key meteorological features with weather maps, standard weather analysis products, and site-specific meteorological data for the modeled time period and domain.[33,39,40] We computed statistical measures to compare WRF values with observed meteorological values using the METSTAT program[41] and evaluated performance by comparing to benchmarks of acceptable model performance.[42] We evaluated CMAQ by comparing simulated concentrations in the 2008 Base Case to EPA federal reference monitor data and by computing statistics recommended for model evaluation.[43−45] We compared these statistical measures to model performance goals and criteria recommended by EPA modeling guidance and prior studies[43,46]

Health Benefits Analysis. We evaluated the health benefits of the S1 and S2 scenario on populations in NYC using the

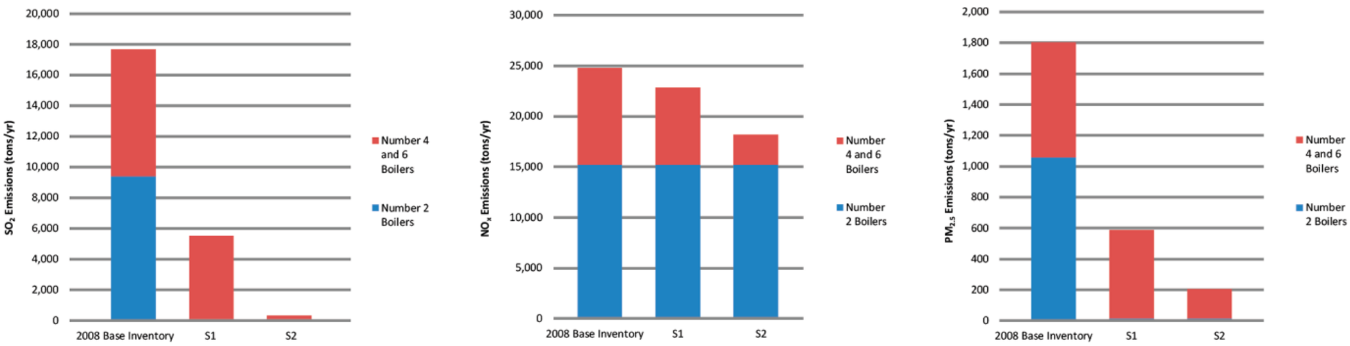

Figure 2. Emissions reductions associated with the S1 and S2 scenarios.

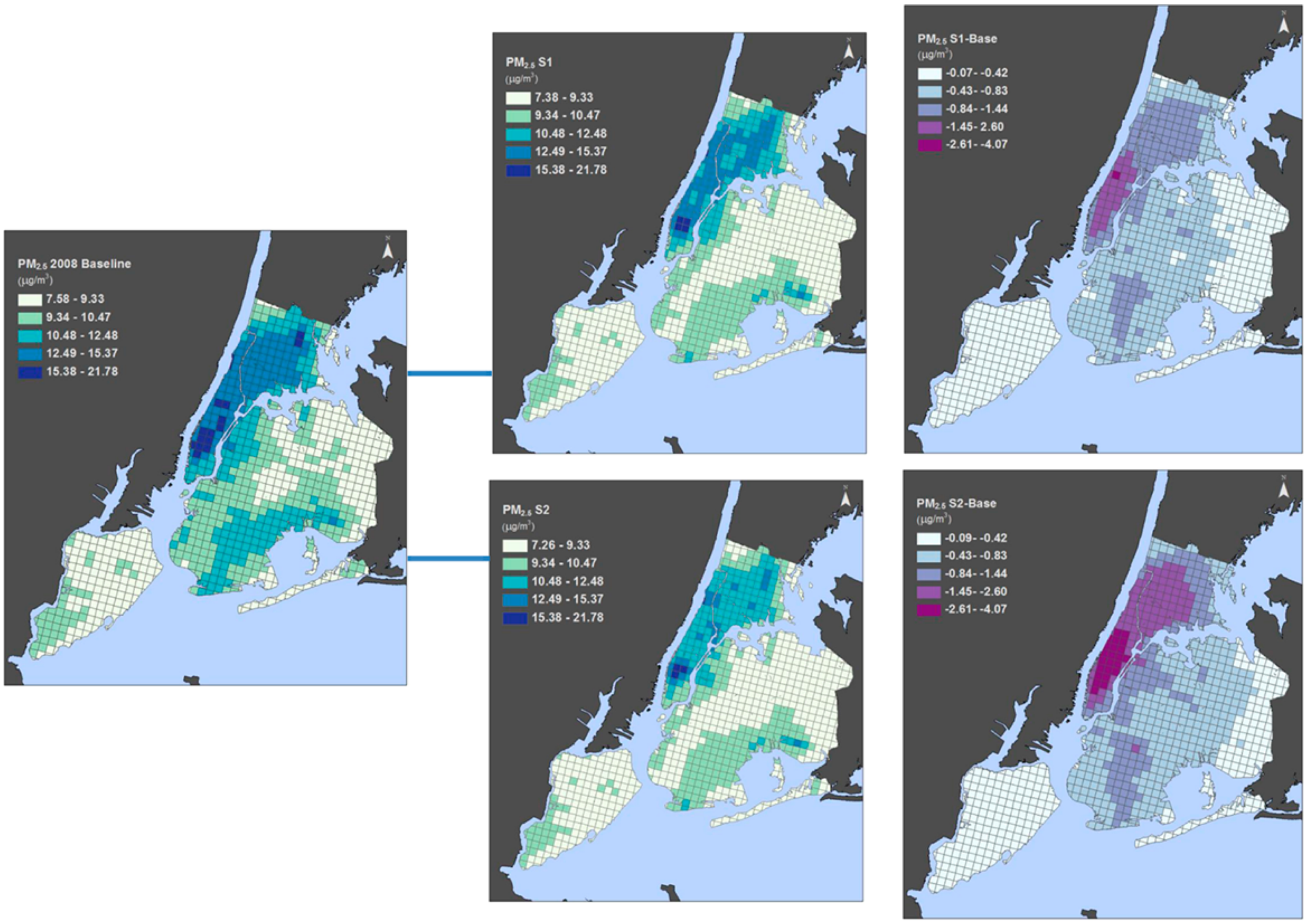

Figure 3. Annual average $PM_{2.5}$ concentrations in 2008 Base Case, S1, and S2 scenarios and change in concentrations due to reduced emissions in each scenario.

CMAQ output from the 1 km resolution grid centered over NYC. We created exposure grids using EPA's Modeled Attainment Test Software (MATS). This method, described in detail elsewhere,[47] provides exposure estimates based on monitored values but leverages the CMAQ output to estimate spatial gradients and responses to the change in emissions associated with the control scenarios on a $PM_{2.5}$ species-specific basis. We developed three-year, quarterly average estimates based on 2008−2010 monitoring and 2008 CMAQ modeling for each of the three scenarios.

A detailed description of methods developed for conducting a local scale $PM_{2.5}$ health impact analysis in NYC have been published elsewhere.[9] Briefly, we estimated the reduction in mortality and morbidity due to changes in $PM_{2.5}$ levels in each scenario (S1 and S2) relative to the 2008 base case using health impact functions that relate the risk of disease or death to ambient concentrations of $PM_{2.5}$. We utilized age-specific risk functions to quantify changes in premature mortality in adults over 30 years of age,[2] emergency department visits for asthma across all ages,[48] hospital admissions for cardiovascular disease in adults over 40 years of age,[49] and hospital admissions for respiratory disease in adults over 20 years of age.[50,51] These risk functions were selected to maintain consistency with previously conducted analyses of $PM_{2.5}$ health burden in NYC[3,9,52]-applying NYC-specific studies when available, and when not, using multicity studies or those included in recent EPA risk

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Table 1. City-Wide Health Benefits of S1 and S2 Control Strategies

health effect	age group	city-wide annual benefit, S1 scenario (reduction in end point counts, (95% confidence interval))[a]	city-wide annual benefit, S2 scenario (reduction in end point counts, (95% confidence interval))[a]
emergency department visits- asthma	all ages	400 (220,580)	550 (300,800)
hospital admissions- cardiovascular conditions	ages 40 and above	60 (10,100)	80 (20,130)
hospital admissions- respiratory conditions	all ages	80 (30,120)	100 (40, 170)
premature mortality	ages 30 and above	210 (140,270)	290 (200,380)

[a]95% confidence interval reflects only the uncertainty from the published epidemiological risk estimate.

analyses. We characterized the baseline population health incidence by computing quarterly 3 year average baseline health rates for 2009−2011 across 22 age and gender groupings for each of 42 United Hospital Fund (UHF) neighborhoods within NYC, matching the ICD-9 codes to those used in the risk estimate of interest. Mortality data was provided by the NYC Department of Health's Bureau of Vital Statistics and hospitalization and emergency room visits data for NYC residents were obtained from the NY Statewide Planning and Research Cooperative System. We used 2009−2011 average population estimates for the same age/sex/neighborhood groupings used in the incidence rates based on the U.S. Census Bureau Population Estimate Program, supplemented by housing data obtained from the NYC Department of City Planning.[53] All health impact calculations were conducted using EPA's Benefits Mapping and Analysis Program (BenMAP) Version 4.067[54] a Geographic Information System based program commonly used for regulatory planning that allows users to estimate the health impacts associated with changes in ambient air quality.

We computed the benefits of the S1 and S2 scenarios relative to the 2008 base case for each quarter (3 year average) in each of the 42 UHF neighborhoods and relevant age/gender groups and then summed impacts to estimate the city-wide, annual benefit of each scenario. Neighborhoods were then grouped into three categories, low poverty, medium poverty, and high poverty, based on the percent of residents earning less than 100% of the federal poverty threshold, from the 2008−2012 American Community Survey.[30] For each group of neighborhoods, average population weighted emissions, average change in $PM_{2.5}$ concentrations, and associated health benefits were computed from the neighborhood-level results and then compared across different levels of neighborhood poverty to evaluate differential impacts across neighborhoods of differing socioeconomic status.

■ RESULTS

Air Quality Benefits. We observed good CMAQ model performance in replicating air quality observations as both CMAQ and WRF performance met recommended bias and precision standards.[33,42,46] The S1 scenario resulted in a reduction of 12 164 tons of SO_2, 1925 tons of NO_x and 1217 tons of primary $PM_{2.5}$ from sources within NYC (Figures 2 and S1). Due to the wide prevalence of No. 2 heating oil boilers in NYC, reduction in their fuel sulfur content accounted for the largest reduction in emissions within the S1 scenario (38% and 7.9% reduction in SO_2 and $PM_{2.5}$ emissions from all sources, respectively). Of the Nos. Four and 6 conversions in S1, 780 boilers switched to natural gas, accounting for the majority of these conversions. The S2 scenario resulted in an additional removal of 5174 tons of SO_2, 4621 tons of NO_x, and 380 tons of primary $PM_{2.5}$. S1 accounts for the majority of the emissions reductions of the program, with 50% of SO_2 emissions removed from the local inventory. After full implementation of all scenarios (S2) a 71.4% reduction in local SO_2 emissions and a 12.1% reduction in local $PM_{2.5}$ emissions are expected.

Based on the MATS-adjusted CMAQ simulation results, the S1 scenario produced reduction in city-wide annual average $PM_{2.5}$ of 0.53 $\mu g/m^3$ (1 km grid cells average), with improvements ranging from 0.11 $\mu g/m^3$ to 1.06 $\mu g/m^3$ across the 10th to 90th percentile of 1 km grid cells (Figure 3). The S2 scenario reduces annual average $PM_{2.5}$ by 0.71 $\mu g/m^3$ city-wide (1 km grid cells average), with improvements ranging from 0.14 $\mu g/m^3$ to 1.57 $\mu g/m^3$ across the 10th to 90th percentile of 1 km grid cells. MATS adjustment of CMAQ was similar across all NYC boroughs (SI Table S1). The largest improvements were seen in areas of highest building and population density, mainly found in Manhattan and parts of the Bronx and Brooklyn, with greatest reductions in the winter (SI Table S2). Relatively less improvement was found in Staten Island and areas of the outer boroughs with fewer boilers and smaller amounts of interior space. Improvements between S1 and S2 were observed in areas of highest residual oil combustion density, mainly in Manhattan and the Bronx. On average, $PM_{2.5}$ levels were 0.18 $\mu g/m^3$ lower in S2 scenario relative to S1.

Health Benefits. Improvements in $PM_{2.5}$ levels due to S1 are estimated to result in 210 avoided premature deaths, 140 avoided hospitalizations for cardiovascular and respiratory disease, and 400 fewer emergency department visits for asthma, annually across NYC (Table 1). These benefits were unevenly distributed throughout NYC, due to the wide variation in underlying population health. The widest ranges in neighborhood benefits were observed for emergency department visits for asthma, where the S1 benefit ranged from 0.2 to 23 cases per 100 000 residents.

Improvements in $PM_{2.5}$ levels due to S2 are associated with 290 avoided premature deaths, 180 avoided hospitalizations for cardiovascular and respiratory disease, and 550 fewer emergency department visits for asthma, annually in NYC (Table 1). Much like the S1 scenario, benefits are unevenly distributed throughout the city, with wide variation in neighborhood benefit.

When classifying the City's neighborhoods by poverty status, we observed the greatest absolute emissions reductions to have occurred in the wealthier neighborhoods of the City, with 16% and 24% greater primary $PM_{2.5}$ emissions reduction for the S1 and S2 scenarios, respectively, in low as compared to high poverty neighborhoods (Table 2). This is due to the high density of buildings using heating oil in populous, affluent

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Table 2. Differences in S1 and S2 Benefits, Relative to Base Case, By Neighborhood Poverty Status

		S1 scenario			S2 scenario		
		low poverty neighborhoods (N = 14)	medium poverty neighborhoods (N = 14)	high poverty neighborhoods (N = 14)	low poverty neighborhoods (N = 14)	medium poverty neighborhoods (N = 14)	high poverty neighborhoods (N = 14)
reduction in Primary $PM_{2.5}$ emissions	total emissions (tons/year)	447.5	378.9	386.0	637.0	441.6	511.0
	emissions density (tons/sqkm-year, population weighted mean)	4.48	1.95	2.57	6.82	2.27	3.49
reduction in $PM_{2.5}$ concentrations	Annual Average ($\mu g/m^3$, population-weighted mean)	0.89	0.63	0.93	1.29	0.8	1.29
emergency department visits for asthma, all ages	baseline incidence rate (events per 100,000 residents)	478	780	1787	478	780	1787
	avoided Incidences (events per 100,000 residents)	2.3	2.6	9.1	3.3	3.3	12.9
	avoided incidences, percent of city-wide benefit (%)	14%	19%	67%	14%	17%	68%
hospitalizations for cardiovascular disease, ages 40 and above	baseline incidence rate (events per 100,000 residents)	1407	1679	1960	1407	1679	1960
	avoided incidences (events per 100,000 residents)	1.3	1.3	2.2	1.8	1.6	3.0
	avoided incidences, percent of city-wide benefit (%)	27%	29%	44%	28%	27%	45%
hospitalizations for respiratory disease, ages 20 and above	baseline incidence rate (events per 100 000 residents)	508	655	875	508	655	875
	avoided Incidences (events per 100 000 residents)	0.9	0.9	1.8	1.3	1.1	2.5
	avoided incidences, percent of city-wide benefit (%)	24%	26%	50%	25%	24%	51%
premature deaths, ages 30 and above	baseline incidence rate (events per 100 000 residents)	890	993	1023	890	993	1023
	avoided incidences (events per 100 000 residents)	4.3	3.4	5.3	6.3	4.3	7.4
	avoided incidences, percent of city-wide benefit (%)	32%	29%	40%	34%	29%	40%

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neighborhoods of Manhattan, such as the Upper East Side and Upper West Side. Similarly, population-weighted average change in emissions density was greater in the higher income neighborhoods, due to similar patterns in population density and boiler density, and high emissions density in more affluent neighborhoods of Manhattan. Alternatively, the change in population-weighted annual average concentrations were relatively even across low and high poverty neighborhoods due to the close proximity of neighborhoods with varying poverty status. Despite similar air quality benefits across neighborhoods of varying poverty status, across all end points considered, the greatest health benefits were observed in high poverty neighborhoods due to the high incidence of morbidity in these communities. We observed approximately 67% and 68% of city-wide avoided asthma emergency department visits in S1 and S2, respectively, to occur in high poverty neighborhoods. Less disparity is seen for avoided premature deaths, where 40% of benefits occur in high poverty neighborhoods.

■ DISCUSSION

Combining local emissions data, boiler conversion tracking, fine-scale photochemical modeling, neighborhood-scale health outcome data, and published concentration−response functions for $PM_{2.5}$, we estimated the city-wide and neighborhood-level public health benefits of programs developed to reduce emissions from the heating sector in NYC. Upon full implementation of heating oil strategies, air quality improvements are expected to result in almost 300 avoided premature deaths and over 700 avoided emergency department visits and hospitalizations for respiratory or cardiovascular causes each year. These benefits are expected to reduce the city's overall $PM_{2.5}$ burden, with predicted improvements accounting for approximately a tenth of current $PM_{2.5}$-attributable mortality. The benefits of these programs were found to be uneven across NYC, with the largest reductions in emissions occurring in more affluent, high population density areas of Manhattan. However, due to the close proximity of high and low poverty neighborhoods and the wide variation in population vulnerability across city neighborhoods, the greatest health benefits of these programs were are estimated to occur in high poverty city neighborhoods.

Evaluation of the S1 scenario demonstrated large public health benefits achieved by State and local emission reduction policies compared to a scenario if no action had been taken. Within this scenario, the majority of the benefits come from the reduction in the sulfur content of No. 2 heating oil with over 1000 tons of primary $PM_{2.5}$ removed and almost 10 000 tons of SO_2 reduced from tens of thousands of properties throughout the city. This analysis demonstrates that continued use of ultralow sulfur No. 2 oil will provide annual health benefits that add to previously demonstrated operational improvements of using lower sulfur heating oils in boilers and furnaces.[15] Additional benefits of the S1 scenario were realized through early conversions of No. 4 and No. 6 boilers prior to conversion deadlines, due in part to outreach and educational programs to provide conversion assistance to building owners and declining natural gas prices that provided a favorable economic climate for natural gas conversions. The air quality benefits of switching within S1 have also been documented through air monitoring data, with declining levels of SO_2 and nickel in $PM_{2.5}$ observed in NYC, markers of combustion of all heating oil and residual oil, respectively.[3]

Although full implementation of NYC heating oil strategies is not required until 2030, we elected to evaluate the benefits of S2 emissions reductions on current populations using recent population estimates and baseline health rates to communicate the public health benefits unrealized each year as boilers wait until the deadline to convert. Using these methods, we estimate that if all remaining boilers could be converted now, hundreds of premature deaths and hospitalizations could be avoided. These significant public health benefits underscore the value of programs to accelerate conversions of No. 4 and 6 boilers ahead of regulatory deadlines and enforcement efforts to ensure boiler switching is occurring on schedule, as these large public health benefits will accrue over time.

To our knowledge this is the first detailed, neighborhood-level analysis of health benefits of heating oil programs in the Northeast. Prior policy analyses of the public health benefits of a Northeast region-wide switch to 15 ppm ultralow sulfur heating oil estimated that close to 200 $PM_{2.5}$-attributable deaths could be avoided in New York State by 2018.[55] While this prior analysis used photochemical modeling and health impact analyses similar to those here, our work extends upon this by using refined local emissions data and neighborhood health incidence data to better reflect population vulnerability, simulating the full suite of ongoing local heating oil measures, and calculating 1 km gradients in exposure changes to estimate the distribution of the benefit across the City's diverse neighborhoods. Other policy evaluations that have used nickel levels monitored by the EPA Speciation Trends Network to estimate the contribution of residual oil to city-wide $PM_{2.5}$ concentrations have estimated up to 260 deaths per year could be avoided through switching all residual oil boilers in NYC commercial and residential buildings.[56,57]

Previous work has demonstrated that accounting for susceptible populations in designing and selecting air quality management strategies can increase area-wide benefits while reducing disparities in pollutant-attributable health effects.[6,8] In creating heating oil conversion mandates, City and State regulators designed policy to reduce emissions from a specific sector, not to target sensitive populations. Nonetheless, our analyses show that despite heating oil emissions reductions in primary $PM_{2.5}$ that are 24% larger in high income neighborhoods relative to low income neighborhoods, upon full implementation of all regulation, the majority of the estimated health benefits in the city occur in high poverty neighborhoods. This is due to the high baseline rate of morbidity in low income neighborhoods as well as the close proximity of neighborhoods with varying socioeconomic status and emissions densities. While traditional environmental justice efforts often focus on addressing specific sources or new facilities within vulnerable communities, these analyses demonstrated benefits to low income neighborhoods in controlling smaller, widely distributed, and perhaps less publicly visible sources in densely developed areas of the city. This approach could be relevant to other cities and to other small, widely distributed, and previously uncontrolled emission sources, such as commercial cooking, which may collectively produce a high density of emissions in close proximity to large vulnerable populations.

As with any complex modeling study with multiple steps and assumptions, the estimates reported here are subject to a variety of limitations. In characterizing emissions from boilers, permit data may be incomplete in some cases or activity data may not reflect actual operating conditions during the year of operation.

The air quality modeling requires a variety of assumptions related to emissions factors, inventories that often estimate emissions using proxy data with varying uncertainty, meteorological models, and spatial and temporal allocation of emissions. However, some of these uncertainties are mitigated by combining monitored and modeled data, thus using the air quality model only for estimating spatial gradients and response to emissions controls. The health impact analysis includes a variety of uncertainties and assumptions inherent in local-scale air quality benefit analyses that have been evaluated elsewhere.[58,59] Some of these uncertainties have been reduced through use of local baseline health data and locally conducted epidemiological studies when available to better characterize underlying health and risks of air pollution exposures. We've applied risk estimates uniformly across the city where there may be variation in risk by neighborhood due to differences in susceptibility. While there are currently no NYC risk estimates that account for within-city population susceptibility, ongoing work is examining the use of stratified time series models or $PM_{2.5}$ constituents to account for neighborhood-level risk modification. Additionally, while the mortality impacts are based on a cohort study that reflects both chronic and acute effects,[60] without a cohort study of morbidity effects applicable to NYC populations, we relied on time series studies, reflecting only short-term outcomes that likely underestimate overall effects that come from chronic exposure. We have also only quantified $PM_{2.5}$ associated premature deaths and hospitalizations and emergency department visits for cardiovascular and respiratory end points which does not account for additional benefits that are expected to come from other avoided end points such as lost work days or from reduced exposures to other pollutants such as SO_2 or NO_x. Finally, this work only quantifies benefits associated with reductions in local air emissions from building heating systems and their impacts on ambient $PM_{2.5}$ and does not account for all ancillary risks and benefits that could come through increased natural gas extraction and reduced heating oil use.

In conclusion, this study describes how an intraurban scale modeling framework was used to evaluate environmental and health benefits of local heating fuel emissions reduction measures. The analysis employed a local heating fuel emissions inventory spatially refined to support a 1 km resolution air quality model in conjunction with neighborhood scale health incidence data. This allowed us to estimate overall environmental and health benefits as well as their distribution within the city, accounting for the steep intraurban gradients of emissions density, population density and neighborhood vulnerability across New York City. The modeling effort—part of a larger suite of strategies and evaluation methods that included a unique, city-wide neighborhood air monitoring program, stakeholder engagement, regulation, incentive programs, and a favorable market for cleaner fuel—provides useful evidence to document to stakeholders and the community the benefits of cleaner heating fuels achieved to date and of continued full implementation of the clean heat measures. We believe the modeling approach used has wider application, in NYC and elsewhere, for assessing strategies to reduce other major local sources of air pollution that are unevenly distributed within urban areas.

■ ASSOCIATED CONTENT

Supporting Information

Online Supporting Information includes maps of boiler emissions associated with the control scenarios, seasonal PM2.5 improvements, and exposure estimates generated by CMAQ and after MATS adjustment. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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