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Co-Benefits to Children's Health of the U.S. Regional Greenhouse Gas Initiative

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BACKGROUND: While various policies have been implemented globally to mitigate climate change and reduce exposure to toxic air pollutants, policy assessments have considered few if any of the benefits to children.

OBJECTIVE: To comprehensively assess the co-benefits of climate change mitigation to children, we expanded the suite of adverse health outcomes in the U.S. Environmental Protection Agency's Benefits Mapping and Analysis Program (BenMAP) to include additional outcomes associated with prenatal and childhood exposure to ambient fine particulate matter ($PM_{2.5}$). We applied this newly expanded program to an assessment of the U.S. Regional Greenhouse Gas Initiative (RGGI), the United States' first regional market-based regulatory program designed to reduce greenhouse gas emissions from the electric power sector within the Northeast.

METHODS: We used calculated changes in ambient $PM_{2.5}$ concentrations for the period 2009–2014, with newly incorporated concentration–response (C-R) functions to quantify changes in the incidence of preterm birth (PTB), term low birth weight (TLBW), autism spectrum disorder (ASD), and asthma. These outcomes are causally or likely to be causally related to $PM_{2.5}$ exposure. Cost per case estimates were incorporated to monetize those changes in incidence.

RESULTS: The estimated avoided cases of adverse child health outcomes included 537 asthma cases, 112 preterm births, 98 cases of ASD, and 56 cases of TLBW, with an associated avoided cost estimate ranging from $191 to $350 million. In a previous analysis of health benefits of RGGI, the only benefits accruing to children were limited to prevented cases of infant mortality and respiratory illnesses, with a monetized impact of $8.1 million—only 2–4% of the new results attributable to RGGI.

CONCLUSION: The results of this innovative analysis indicate that RGGI has provided substantial child health benefits beyond those initially considered. Moreover, those health benefits had significant estimated economic value. https://doi.org/10.1289/EHP6706

Introduction

Toxic air pollutants such as ambient fine particulate matter [PM $\leq 2.5\ \mu m$ in aerodynamic diameter ($PM_{2.5}$)] and the major climate-altering gas, carbon dioxide (CO_2) emitted by fossil fuel combustion, are taking a significant toll on children's health and jeopardizing their future well-being. They are also major contributors to inequality worldwide (Perera 2017). Because of their biological vulnerability and rapid development, the developing fetus and young child are disproportionately affected by air pollution and climate change (Perera 2017). This is especially true in populations where poverty and environmental injustice compound the effects. A number of climate change mitigation policies and air pollution regulations have been implemented around the world to reduce fossil fuel combustion emissions, with sizeable health and economic benefits documented or projected. However, assessments of the public health benefits of such policies have considered few, if any, benefits to children; and their lifelong consequences have generally not been factored into the assessments of avoided costs. These include the U.S. Clean Air Act Amendments (U.S. EPA 2011), the Clean Power Plan (Driscoll et al. 2015), California's cap and trade program and low-cost fuel standards (O'Connor et al. 2014), the City of London Air Quality Strategy (City Of London Corporation 2019), and the Paris Climate Accord (Markandya et al. 2018). This omission has resulted in a serious undercounting of potential health benefits for this vulnerable population.

The Regional Greenhouse Gas Initiative (RGGI) is the United States' first regional market-based regulatory program designed to reduce greenhouse gas emissions from the electric power sector (RGGI Inc. 2019a). RGGI was established in the northeastern region in 2005 through a Memorandum of Understanding between the governors of Connecticut, Delaware, Maine, New Hampshire, New Jersey, New York, and Vermont. In 2007, the program was expanded to include Maryland, Massachusetts, and Rhode Island, and in 2008 it held an initial auction for emissions allowances (Center for Climate and Energy Solutions 2019). Under RGGI program, participating states are expected to reduce their annual CO_2 emissions from the power sector by 45% below 2005 levels by 2020, and by an additional 30% by 2030 (Center for Climate and Energy Solutions 2019). RGGI included 10 states during its initial compliance period starting in 2009. The program is still currently operating with 9 of the original states, with New Jersey having withdrawn in 2012 but planning to rejoin in 2020 (Center for Climate and Energy Solutions 2019).

RGGI places limits on CO_2 emissions from new and existing fossil-fuel-fired electric generating units (EGUs) in the program area with a minimum capacity of 25 MW. Regulated EGUs must obtain allowances for each short ton of emitted CO_2. Allowances are auctioned quarterly and may be sold or traded between EGUs. Auction revenues have been reinvested to accelerate renewable energy use, improve energy efficiency, and support other public benefit programs (RGGI Inc. 2019a).

Although RGGI is focused on reducing greenhouse gas emissions, it also reduces emissions of other pollutants, such as $PM_{2.5}$, nitrogen oxides (NO_x), and sulfur dioxide (SO_2) (Manion et al. 2017). NO_x and SO_2 react in the atmosphere to form $PM_{2.5}$, which has a well-documented relationship with multiple adverse health outcomes, including respiratory and cardiovascular effects, premature mortality, and, more recently, adverse birth outcomes,

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respiratory illness, and neurodevelopmental problems in children (Perera et al. 2019).

Abt Associates previously analyzed health impacts of the first two compliance periods of RGGI (2009–2014) (Manion et al. 2017). The analysis estimated the reduction in NO_x and SO_2 emissions from RGGI-influenced EGUs based on modeling of the electricity sector and used the U.S. Environmental Protection Agency's (EPA's) Co-Benefits Risk Assessment (COBRA) to estimate changes in ambient levels of secondarily formed $PM_{2.5}$. The Environmental Benefits Mapping and Analysis Program (BenMAP) tool was used to estimate associated changes in health benefits due to changes in the ambient concentration of $PM_{2.5}$ in the nine then current RGGI states and in the adjacent states of New Jersey, Pennsylvania, Virginia, and West Virginia. BenMAP is a publicly available computer program supported by the U.S. EPA that can be used to estimate the number of air pollution-related illnesses and deaths and quantifies their economic value (U.S. EPA 2019). The program draws from a database that includes concentration–response (C-R) functions for a number of health outcomes attributable to different pollutants, population data, baseline health data, and cost of illness functions needed to quantify impacts (U.S. EPA 2019). The C-R functions included by default in the open-source program are focused largely on health outcomes for adults and do not currently include C-R functions or data for the children's health outcomes newly considered here.

Abt's 2017 assessment focused on avoided cases of premature adult deaths, heart attacks, acute bronchitis, asthma exacerbations, respiratory symptoms, hospitalizations, asthma emergency department visits, as well as productivity effects such as lost work days and days of minor restricted activity (Manion et al. 2017). These end points have traditionally been included in the U.S. EPA's regulatory analyses such as the *Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter* (U.S. EPA 2012). The 2017 assessment found that between 2009 and 2014, emissions reductions from RGGI resulted in avoided health outcomes having an estimated value of between $3 billion and $8.3 billion (2015$).

Since Abt's original analysis, the evidence base has strengthened the relationship between $PM_{2.5}$ and additional health end points, particularly end points that affect children. Specifically, Perera et al. (2019) conducted a systematic review of epidemiological studies quantifying the impacts of changes in ambient $PM_{2.5}$ concentrations on health end points identified as having a causal or likely causal relationship with $PM_{2.5}$: preterm birth (PTB), term low birth weight (TLBW), autism spectrum disorder (ASD), and incidence of asthma. Based on this review, the authors selected odds ratios that could be used to develop C-R functions for each outcome in estimating the benefits of reducing $PM_{2.5}$ exposure.

The present analysis provides a more comprehensive evaluation of children's health benefits under RGGI by including these additional health end points. This involved incorporating C-R functions for the new health end points and data on baseline incidence of these end points into BenMAP. These inputs were used with emissions reductions and air quality modeling results from the 2017 RGGI analysis to estimate the impacts of RGGI on PTB, TLBW, ASD, and asthma between 2009 and 2014 in RGGI states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont) and adjacent non-RGGI states (Pennsylvania, the District of Columbia, New Jersey, Virginia, and West Virginia). Per-case monetary estimates (unit values) were incorporated into the expanded BenMAP based on a systematic review of the published literature on the cost of illness (Shea et al. 2020).

In addition, in order to more fully present the impacts/benefits in children, this report highlights the change in incidence of infant mortality, acute bronchitis, and respiratory symptoms in children included in the results of the 2017 analysis. However, these were not explicitly reported as occurring in children.

Methods

This section describes in detail the methods and data sources used to quantify and monetize the change in incidences of PTB, TLBW, ASD, and childhood asthma. Both RGGI states and adjacent non-RGGI states were included in the analysis.

Figure 1 summarizes the general analytic approach used in Abt's 2017 RGGI analysis (Manion et al. 2017). Step 1 involved estimating the change in NO_x and SO_2 emissions at the county-level based on electricity dispatch modeling conducted by the Analysis Group, an economics consulting firm, which included the change in electricity generation by EGUs under two scenarios: with RGGI and without RGGI. Abt then estimated the change in emissions due to the change in generation based on facility-specific emissions rates from U.S. EPA data. In Step 2, Abt used COBRA, a screening-level tool, which includes a reduced-form air quality model to estimate how changes in NO_x and SO_2 emissions would impact ambient concentrations of $PM_{2.5}$ in RGGI and neighboring states. The estimated incremental changes in NO_x and SO_2 emissions calculated in Step 1 were used to model changes in concentrations during individual years (2009–2014). Outputs from this model included annual changes in levels of ambient $PM_{2.5}$ in each county in RGGI and neighboring states and were the inputs for modeling the associated health impacts. Finally, in Step 3, Abt used the expanded BenMAP to estimate how changes in ambient $PM_{2.5}$ concentrations resulted in changes in health impacts in children.

The present analysis made no changes to Steps 1 and 2 from the 2017 analysis—we obtained annual average $PM_{2.5}$ concentration data from Abt Associates for the years 2009–2014. Rather, the present analysis added additional health end points to BenMAP and estimated how the modeled changes in $PM_{2.5}$ concentrations under RGGI (2009–2014) affected those additional end points. The remainder of this section discusses the specific inputs and steps taken in this analysis.

C-R Functions

C-R functions are estimates of the relationship between changes in ambient pollutant concentrations and incidences of specific health end points. These functions are derived from epidemiological studies that compare the change in incidences of specific health outcomes to, in this case, changes in ambient $PM_{2.5}$ concentrations.

Perera et al. (2019) conducted a systematic review of epidemiological studies, meta-analyses, and review articles to determine the current state of the science on the associations of ambient air pollutants, including $PM_{2.5}$, and children's health outcomes. Through this comprehensive review the authors identified four key meta-analyses that estimated the relationship between changes in $PM_{2.5}$ concentrations and changes in the incidence of each health end point (Table 1).

We used the results of Perera et al. (2019) to incorporate C-R functions for each end point into BenMAP. The C-R functions include a beta coefficient, which quantifies the impact on each health outcome per 1-unit change in $PM_{2.5}$ concentrations. We developed the beta coefficients shown in Table 1, based on the natural log of the odds ratio reported by the meta-analysis, divided by the reported exposure change (in micrograms per cubic meter), as is consistent with U.S. EPA practice (U.S. EPA 2012). The beta coefficients were combined with county-level data on

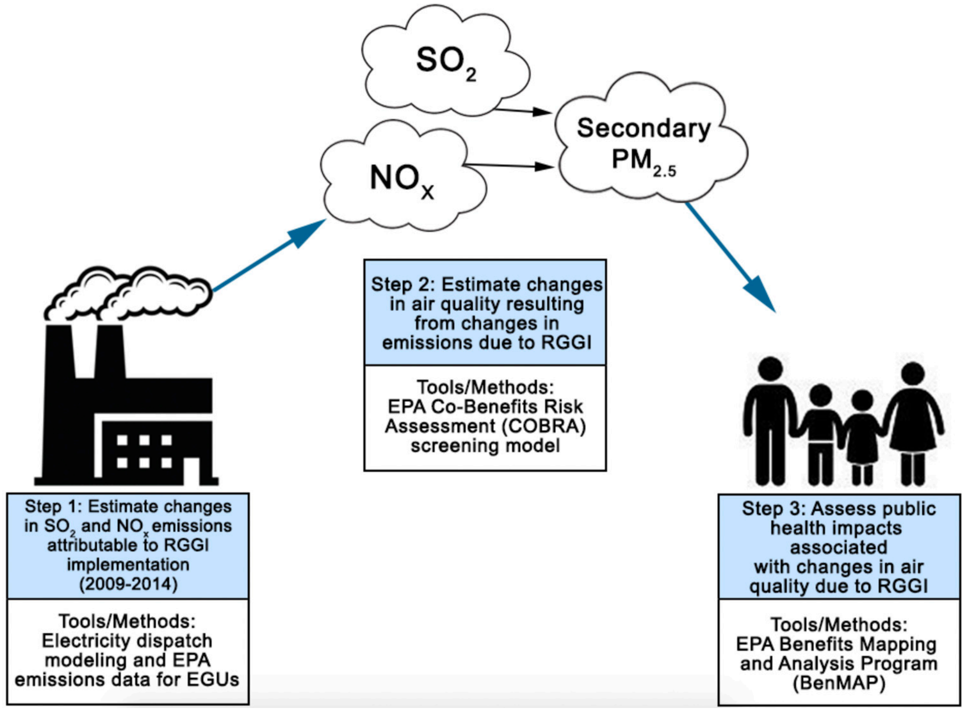

Figure 1. Overview of the analytic steps and tools. Source: Manion et al. 2017. Note: EGU, electric generating unit; EPA, Environmental Protection Agency; NO_x, nitrogen oxides; $PM_{2.5}$, particulate matter ≤2.5 μm in aerodynamic diameter; RGGI, U.S. Regional Greenhouse Gas Initiative; SO_2, sulfur dioxide.

population, baseline incidence, and the modeled change in county-level $PM_{2.5}$ concentrations to estimate the change in incidence of each health outcome in each county.

Population

The impact assessments require data on the affected age groups in the population. For this analysis, we used the county-level population by age group data loaded in BenMAP for each year of the analysis (2009–2014). These data were taken from the 2010 U.S. Census of Population and Housing models (developed by Woods and Poole 2011).

The C-R functions for PTB, low birth weight (LBW), and ASD reported in Perera et al. (2019) are based on maternal exposure during pregnancy. We applied the C-R functions to the population in Age Group 0 in BenMAP, which was used as a proxy for pregnant mothers. The C-R function for asthma incidence is based on the exposure of children under the age of 18 y. Accordingly, we applied this C-R function to populations in Age Groups 0–18.

Table 1. Meta-analyses for additional health end points associated with $PM_{2.5}$ identified by Perera et al. (2019).

Health end point	Study	Odds ratio	Exposure metric	Beta coefficient
PTB	Sun et al. 2015	1.13	Per 10-μg/m^3 increase	0.012
LBW	Sun et al. 2016	1.09	Per 10-μg/m^3 increase	0.009
ASD	Lam et al. 2016	2.32	Per 10-μg/m^3 increase	0.084
Asthma incidence	Khreis et al. 2017	1.03	Per 1-μg/m^3 increase	0.030

Note: Perera et al. (2019) conducted a systematic review to determine the current state of the science on the associations of ambient air pollutants, including $PM_{2.5}$, and children's health outcomes. The authors identified four key meta-analyses that estimated the relationship between $PM_{2.5}$ concentrations and the incidence of each health end point: PTB, LBW, ASD, and asthma. ASD, autism spectrum disorder; LBW, low birthweight; $PM_{2.5}$, particulate matter ≤2.5 μm in aerodynamic diameter; PTB, preterm birth.

Baseline Incidence

Baseline incidence rates for each end point were drawn from public data sources and the academic literature. County-level incidence rates of PTB and LBW were taken from the Centers for Disease Control and Prevention (CDC) WONDER database (CDC 2019), which contains extensive data on births, including gestational age and infant birth weight.

PTB is defined as a birth that occurs before the 37th week of pregnancy. The incidence of PTB was developed by dividing the number of births in each county occurring before the 37th week of pregnancy by the total number of births in each county. The county-level average incidence rate of PTB in RGGI and neighboring states was 13.4%. For comparison, the national average rate was 11.6%.

TLBW is defined in this analysis as a weight <2,500 g at birth when the infant was delivered on or after the 37th week of pregnancy (i.e., early to late term). This analysis does not include LBW in infants born before the 37th week of pregnancy to avoid double-counting the effects of PTB. The incidence of TLBW was calculated by dividing the number of full-term births in each county where the weight of the infant was <2,500 g by the total number of full-term births in each county. The county-level TLBW rate average was 3.2%. For comparison, the national TLBW rate average was 3.3%.

In the absence of county-level and complete state-level data, the asthma incidence rate for this analysis was taken from Winer et al. (2012), who estimated a national rate of 11.1 per 1,000 children ages 5–11 y from 2006–2008. This estimate was based on the Asthma Call-Back Survey, which was first implemented in 2006. Incident cases of asthma were defined as children diagnosed with asthma by a health care provider within 12 months prior to survey participation.

Because incidence rates were not directly available for ASD, we used prevalence as a proxy. In the absence of county-level and complete state-level data for prevalence, we selected the national prevalence rate of ASD for 2014 based on a CDC report (Zablotsky et al. 2015). We note that incidence is difficult to measure with rarer chronic diseases such as autism. In addition, the disorder starts long before it is diagnosed, and the gap between initiation and diagnosis is influenced by many factors unrelated to risk (Hertz-Picciotto and Delwiche 2009). The rate used in this analysis was 14.7 per 1,000 children (Zablotsky et al. 2015).

Economic Valuation

The economic value of the change in incidences of each health end point was estimated using unit cost values from the literature (Shea et al. 2020). As described, those values were adjusted to 2015$ using a discount rate of 3% (Shea et al. 2020). Table 2 lists the values used in this analysis and the studies from which they were taken. The economic costs of each health end point were estimated by multiplying the change in incidences, as estimated by BenMAP, by the values in Table 2.

The values for asthma and ASD in Table 2 include high and low values. For asthma this is related to whether or not there is a persistence of the disorder into adulthood. For ASD this is related to whether there is an intellectual disability or not. For these end points, both the high and low values were used, and the results are reported as a range.

Results

This section describes the results of the analysis, including the estimated change in incidences of each health end point (the number of avoided cases) due to the emissions reductions associated with RGGI, as well as the economic valuation of those changes in incidences. Both the change in incidences and the economic valuation are summarized as the cumulative change between the year 2009 and the year 2014 (for both RGGI and neighboring states). The results are summarized separately for RGGI and neighboring states, and then totaled.

The results of this analysis are also compared with the results of the previous RGGI analysis (Manion et al. 2017), specifically the other health end points in children that were included in the previous analysis but not all explicitly labeled as occurring in children.

Change in Incidences

Table 3 shows the estimated change in incidence—the estimated number of avoided cases—of each health end point in RGGI and neighboring states between 2009 and 2014. Asthma had the largest change in incidence, at 537 cases avoided in the study area between the year 2009 and the year 2014. TLBW had the lowest change in incidence, at a total of 56 incidences avoided. This largely reflected that LBW had the smallest beta coefficient of the four end points (Table 1).

Table 3. Number of estimated avoided cases by health end point in RGGI and neighboring states (2009–2014).

Health end point	RGGI states	Neighboring states	Total
PTB	58	54	112
TLBW	29	27	56
ASD	50	48	98
Asthma	274	263	537

Note: RGGI states include Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont. Adjacent non-RGGI states include Pennsylvania, the District of Columbia, New Jersey, Virginia, and West Virginia. ASD, autism spectrum disorder; PTB, preterm birth; RGGI, U.S. Regional Greenhouse Gas Initiative; TLBW, term low birth weight.

Economic Valuation

Table 4 shows the results of the economic valuation of the change in incidences in RGGI and neighboring states between 2009 and 2014 for the newly incorporated health end points: ASD, asthma, TLBW, and PTB. As discussed above, both ASD and asthma have high and low estimates for the economic values of each end point. Results using both the high- and low-end estimates are shown here.

Although ASD was estimated to have the second-lowest number of avoided incidences compared with other health end points, it had by far the highest valuation per case, estimated at $1.8–3.1 million (Table 2). As a result, the economic valuation of the reduction in ASD incidences accounted for 84–89% of the total health benefits of the four health end points. Although asthma had a lower valuation per end point, it had the highest estimated change in incidence, leading it to have the second-highest value of the four health end points, at 6–13% of the total health benefits of those four end points. PTB and TLBW both had relatively lower per-unit economic values and lower estimated change in incidences. Therefore, the estimated economic valuation for those end points was comparatively smaller: 2–4% of the total benefits for PTB and <1% for TLBW.

Table 2. Per-case monetary estimates of each health end point (Shea et al. 2020).

Study basis	Health end point	Cost of illness definition	Unit value (2015$)
PTB			
Institute of Medicine Committee on Understanding Premature Birth and Assuring Healthy Outcomes 2007	Any PTB	Medical costs + special education costs + lost productivity costs, 3% discount rate (DR)	70,101
LBW			
Russell et al. 2007	LBW among those with slow growth/malnutrition	Initial hospital costs	15,560
ASD			
Buescher et al. 2014	ASDs with intellectual disability	Medical costs + non-medical expenditures + special education costs + lost productivity costs, 3% DR	3,109,096
	ASDs without intellectual disability	Medical costs + non-medical expenditures + special education costs + lost productivity costs, 3% DR	1,805,941
Asthma			
Nurmagambetov et al. 2018	Age 3 y onset, no persistence into adulthood	Medical costs + absentee costs, 3% DR	23,573
	Age 3 y onset, persistence into adulthood	Medical costs + absentee costs, 3% DR	91,954

Note: The values for asthma and ASD include high and low values. For asthma this is related to whether or not there is a persistence of the disorder into adulthood. For ASD this is related to whether there is an intellectual disability or not. For these end points, both the high and low per-case monetary estimate values were used, and the results are reported as a range. ASD, autism spectrum disorder; LBW, low birth weight; PTB, preterm birth.

Table 4. Estimated economic valuation (million 2015$) of change in incidence by health end point in RGGI and neighboring states (2009–2014).

	Low value			High value		
Health end point	RGGI states	Neighboring states	Total	RGGI states	Neighboring states	Total
ASD	87.3	83.7	171.0	150.2	144.1	294.4
Asthma	6.2	5.9	12.1	24.2	23.1	47.4
TLBW	0.4	0.4	0.8	0.4	0.4	0.8
PTB	3.9	3.6	7.5	3.9	3.6	7.5
Total	97.8	93.7	191.5	178.8	171.3	350.1

Note: The values for asthma and ASD include high and low values. For asthma this is related to whether or not there is a persistence of the disorder into adulthood. For ASD this is related to whether there is an intellectual disability or not. For these end points, both the high and low per-case monetary estimate values are used, and the results are reported as a range. ASD, autism spectrum disorder; PTB, preterm birth; RGGI, U.S. Regional Greenhouse Gas Initiative; TLBW, term low birth weight.

Comparison of Current Results to Estimates from the Previous (2017) Analysis

The 2017 Abt analysis of the health benefits of RGGI estimated total health benefits of between $3.0 billion and $8.3 billion between 2009 and 2014, using a 3% discount rate (Manion et al. 2017). This included an estimated 300–830 avoided premature adult mortalities, which accounted for the great majority of the monetized benefit.

The economic value of the health benefits of the four health end points in the present analysis were estimated at between $191 million and $350 million, or approximately 4–6% of the total benefits of the 2017 analysis, but considerably larger than the originally estimated impact from health outcomes excluding premature mortality.

Although the 2017 analysis did not specifically report benefits that accrue to adults and children separately, some of the health end points included in that analysis were focused on children. Specifically, the child-focused health end points included infant mortality, acute bronchitis, and respiratory symptoms. The numbers of estimated avoided incidences and economic valuation of those incidences are shown in Table 5. Note that the 2017 analysis included some health effects that applied to both children and adults, such as asthma emergency department visits and respiratory hospital admissions. Because it was not possible to separate out the impacts in children, those results are not discussed here.

As shown in Table 5, the economic value of the estimated health benefits to children from the 2017 analysis is dominated by avoided infant mortality. Although the estimated incidence was <1, the economic value per incidence is so high (approximately $11 million per incidence) that it vastly outweighs the economic value of the other health end points, which have per-incidence economic values of <$1,000 each.

The four health end points for children included in the 2017 analysis (Table 5) have a much lower total economic value than the four health end points in the present analysis (Table 4). The economic value of the benefits to children included in the 2017 analysis are approximately 2–4% the size of the value of the benefits to children newly included in the present analysis.

The total health benefits to children from RGGI between 2009 and 2014, including all eight health end points (both those in the 2017 analysis and the present analysis), were estimated at $199.6–358.2 million.

Table 5. Estimated health benefits for children due to RGGI (2009–2014) from the previous Abt Associates analysis [RGGI and neighboring states (Manion et al. 2017)].

Health end point	Avoided incidences	Economic value (million 2015$)
Acute bronchitis	510	0.30
Infant mortality[a]	<1	7.30
Lower respiratory symptoms	6,500	0.17
Upper respiratory symptoms	9,300	0.37
Total[b]	16,310	8.10

Note: BenMAP, Benefits Mapping and Analysis Program; RGGI, U.S. Regional Greenhouse Gas Initiative.

[a] The 2017 analysis estimated <1 avoided infant mortality due to RGGI. It is important to note that the C-R functions in BenMAP estimate actual health outcomes based on the change in risk of an outcome. Therefore, estimating <1 avoided infant mortality means that RGGI reduced the risk to infants by a relatively small, although not negligible, amount. Nevertheless, this reduced risk still has a very high economic value relative to the other health outcomes.

[b] Totals may not sum due to rounding.

Distributional Analysis of Benefits across Counties

The map in Figure 2 shows considerable variation across RGGI and neighboring counties in the distribution of economic benefits from the cumulative avoided child health outcomes: PTB, TLBW, ASD, asthma, infant mortality, acute bronchitis, lower respiratory symptoms, and upper respiratory symptoms.

Figure 3 maps the spatial distribution of reductions in average annual $PM_{2.5}$ concentrations between 2009 and 2014 at the county level attributable to RGGI during its first and second compliance periods. These results show substantial air quality benefits, particularly in counties downwind of Maryland's power plants regulated under RGGI. In addition, counties in New Jersey and Pennsylvania, both currently non-RGGI states, experienced significant air quality improvements attributable to emission reductions in neighboring RGGI states.

It is important to note that estimates of reductions in $PM_{2.5}$ concentration represented in Figure 3 account only for secondary $PM_{2.5}$ formed by chemical reactions of NO_x and SO_2. This analysis does not account for impacts of directly emitted $PM_{2.5}$. Nor does it account for the health effects from other pollutants such as ozone (O_3) or nitrogen dioxide (NO_2), thereby underestimating the health benefits under RGGI.

Discussion

Over the past decade, RGGI has driven significant emission reductions from the electric power sector. The program's initial goal was to reduce annual power sector CO_2 emissions by 45% below 2005 levels by 2020. Their 2030 goal was to reduce emissions by an additional 30% (Center for Climate and Energy Solutions 2019). According to a recent report by RGGI, by 2017, participating states had reduced CO_2 emissions from the power sector by more than 50% since 2005 while maintaining steady regional gross domestic product growth (RGGI Inc. 2019b), suggesting that RGGI states have exceeded their initial goal and are on track to meet their 2030 goal. Additional findings from a 2019 assessment (Acadia Center 2019) indicate that since 2008 (1 y prior to the program's launch), RGGI states' emissions from the electric power sector decreased from 133 million short tons of CO_2 to 70 million; these reductions exceeded those of the rest of the country by 90% (Acadia Center 2019). Although RGGI has not been the single driver behind the northeastern region's decarbonization in the electric power sector, a previous analysis (Murray and Maniloff 2015) has suggested that the program has

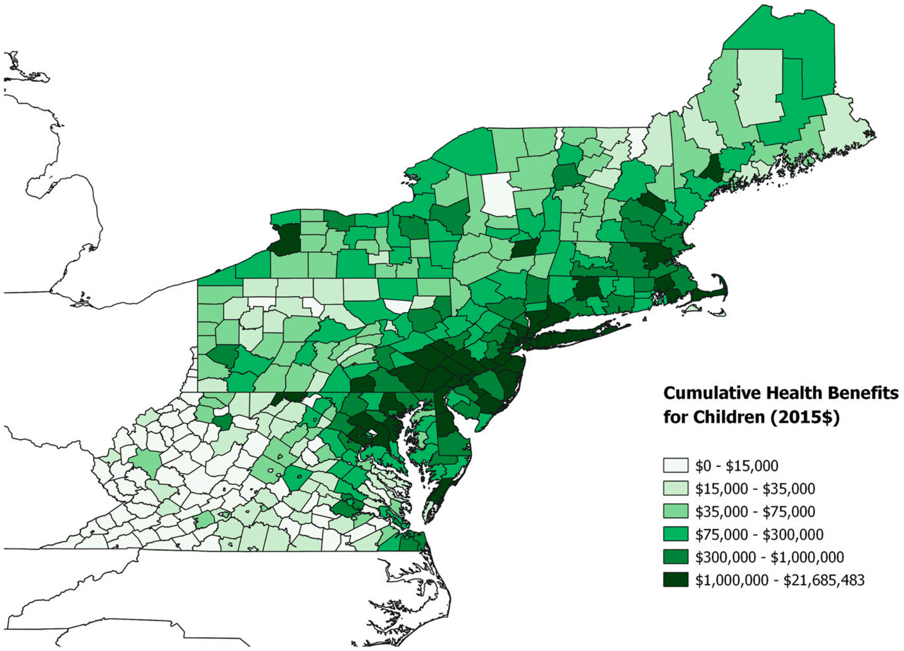

Figure 2. Economic benefits of avoided cases of child health outcomes attributable to RGGI by county, 2009 to 2014 (low value, 2015$). Note: RGGI, U.S. Regional Greenhouse Gas Initiative.

been a significant factor in the reduction of power plant emissions. Simulations from that analysis also suggested that emissions would have been approximately 24% higher in the region and 1.4% higher in the United States in 2012 without the program's implementation in 2009 (Murray and Maniloff 2015).

The results of our analysis of RGGI's co-benefits from the reduction in air pollution indicate that RGGI has provided substantial child health benefits beyond those considered in the 2017 analysis. Moreover, those health benefits have significant estimated economic value. The previous analysis found large total health benefits with a total economic value of \$3.0–8.3 billion; nearly all of those benefits were due to avoided adult mortality (Manion et al. 2017). The benefits from health end points specific to children included in the 2017 analysis (infant mortality, acute bronchitis, and other respiratory symptoms) were estimated at \$8.1 million, accounting for a very small fraction (0.09–0.27%) of the total estimated health benefits. The four additional health end points considered here—PTB, TLBW, ASD, and asthma—have a much larger combined economic value (\$191–350 million) than those previously considered and amount to 4–6% of the total adult and child benefits from the 2017 analysis. This is likely to be an underestimate, as discussed below. Of the four additional health end points, asthma had the most significant change in incidence (number of avoided cases) between 2009 and 2014. This is expected, given that the C-R function used to estimate the incidence of asthma was applicable to all children ages 0–18 y, while the C-R functions for the other health end points were applied only to infants (age 0 y). As a result, there is a larger population of children for whom the analysis estimated impacts on the incidence of asthma.

Although a modest contribution to the total avoided costs, estimates from the present study are 20–40 times greater than the value of the avoided child outcomes in the 2017 analysis (Manion et al. 2017). The estimated total economic benefit from these avoided cases attributed to RGGI between 2009 and 2014, including the combined eight health end points considered in the 2017 analysis and the present analysis, was \$199.6–358.2 million.

Not only is this a substantial economic benefit, but it is likely an underestimate of the true benefit because the adverse outcomes in children associated with $PM_{2.5}$ not only have immediate heath impacts but can also have serious consequences for their future health, well-being, and ability to contribute to society. These long-term health or lifelong consequences are not adequately considered in most of the outcome valuations used in this analysis.

In addition, it is important to note that the per-case estimates used in our calculations of avoided costs are likely underestimates for a few reasons, including the reliance on the cost of illness (COI) (Shea et al. 2020). For instance, as the U.S. EPA *Guidelines for Preparing Economic Analyses* notes, the COI method for developing per-case estimates typically does not attempt to quantify a loss in utility from pain and suffering (U.S. EPA 2010). Given that these costs are often omitted from COI estimates, the value of an individual's willingness to pay to avoid a lifetime of an illness like asthma may be significantly larger than the COI value. Furthermore, potential long-term costs to children or parents were not generally considered in the per-case monetary estimates used in this study (Shea et al. 2020). Examples are a child's cognitive disability associated with PTB and the impact on parents' employment behaviors, affecting their household income (Petrou et al. 2001).

A further factor in potentially significant underestimation of benefits is that both the 2017 and the present analyses include only emission reductions of NO_x and SO_2. Although secondary $PM_{2.5}$ accounts for the majority of $PM_{2.5}$ resulting from power plant emissions (NARSTO 2004), the analysis did not consider impacts from directly emitted $PM_{2.5}$. Nor were the health benefits of reductions in O_3 precursors, NO_2, and climate-altering greenhouse gases factored into this analysis. For these reasons, the results are conservative.

The health benefits from RGGI are not likely to be evenly distributed geographically, with some populations receiving higher health benefits than others. This analysis (like Manion et al. 2017) estimated the geographic distribution of health benefits by county but did not attempt to estimate disparities in health benefits by differences in socioeconomic status or ethnicity/race. This is because air quality results used in this analysis (and the previous 2017 analysis) are at the county level, and socioeconomic

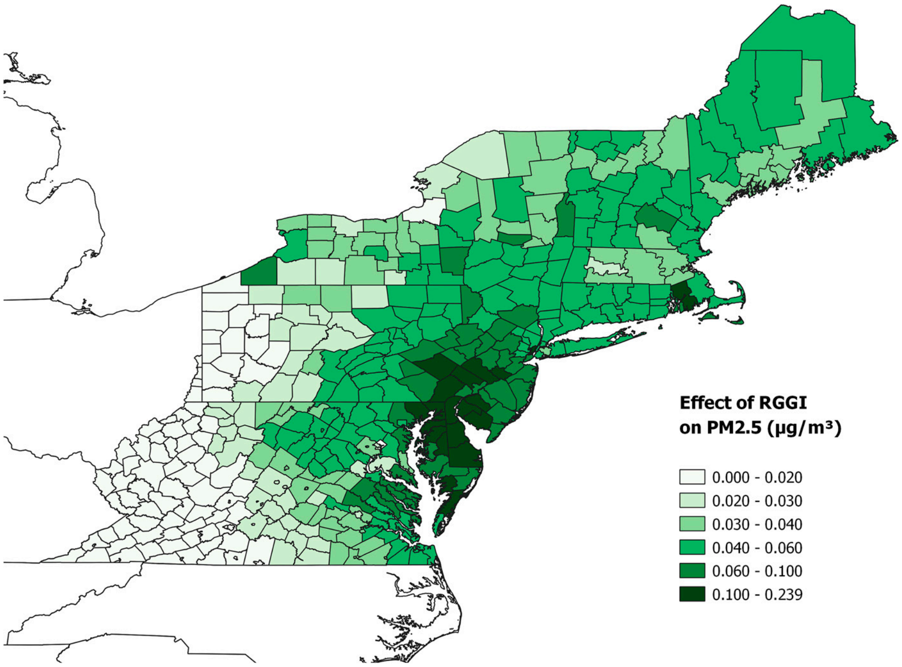

Figure 3. Reductions in average annual $PM_{2.5}$ concentrations by county attributable to RGGI (2009–2014) Source: Abt Associates 2017. Estimates of reductions in $PM_{2.5}$ concentration account only for secondary $PM_{2.5}$ formed by chemical reactions of NO_x and SO_2. This analysis does not account for impacts of directly emitted $PM_{2.5}$. Nor does it account for the health effects from other pollutants such as O_3 or NO_2, thereby underestimating health benefits under RGGI. Note: NO_x, nitrogen oxides; NO_2, nitrogen dioxide; O_3, ozone; $PM_{2.5}$, particulate matter ≤ 2.5 μm in aerodynamic diameter; RGGI, U.S. Regional Greenhouse Gas Initiative; SO_2, sulfur dioxide.

status and distribution of population by ethnicity/race can vary widely within counties (Sommeiller et al. 2016).

Exploratory assessment of the distributional impacts of the health benefits and associated economic benefits at the county level showed significant variation in benefits across counties, as demonstrated in Figure 2. The monetized benefits are a function of the change in air quality and the total population affected. As a result, more densely populated areas would be expected to have higher benefits because there is a larger at-risk population (more pregnant women and children) breathing cleaner air. This is likely occurring in densely populated counties across New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, and New Jersey. Reductions in average annual $PM_{2.5}$ concentrations between 2009 and 2014 under RGGI, as shown in Figure 3, suggest substantial air quality benefits.

A comparison of the two maps (Figures 2 and 3) gives a sense of the magnitude of the air quality changes experienced in each county relative to their corresponding health benefits. Similar to the economic benefits map (Figure 2), the map of reductions in $PM_{2.5}$ concentrations (Figure 3) shows considerable variation across counties. In most counties, the distribution of economic benefits corresponds with reductions in levels of $PM_{2.5}$; highlighting the direct benefit from emission reductions. On the other hand, as shown in Figure 3, some counties—for example, in Massachusetts, Connecticut, and Rhode Island—experienced disproportionately high estimated health and economic benefits in relation to their low level emission reductions; indicating that even slight reductions in $PM_{2.5}$ emissions resulted in considerable benefit.

Because of the scale of analysis, we were not able to meaningfully examine whether benefits were shared equitably across socioeconomic strata and different racial/ethnic populations. This is a major concern with respect to environmental justice given that it is the less affluent communities and communities of color that have borne the brunt of fossil fuel–related pollution and climate change impacts (Morello-Frosch et al. 2011). Although regional cap and trade policies like RGGI may be effective in reducing greenhouse gases and their co-pollutants on a regional scale, they may not maximize public health benefits or adequately address existing environmental justice issues. A more granular analysis (e.g., at the census tract or neighborhood level) is necessary to better understand finer-grained changes in air quality and the true distribution of health benefits by population density, socioeconomic status, and ethnicity/race. Such a comprehensive assessment could provide an opportunity to evaluate whether alternative programs could achieve the same greenhouse gas mitigation goals while also redressing environmental injustice.

As noted by Manion et al. (2017), the benefits associated with reducing emissions of the major greenhouse gas, CO_2, are outside of the scope of this study. Thus, the analysis does not cover the many health benefits of mitigating climate change, such as fewer heat-related illnesses or cases of vector-borne disease to which children are especially vulnerable. In addition, benefits to ecosystems and natural resources that support human livelihood are not captured in this analysis.

Because the epidemiologic evidence on the association between $PM_{2.5}$ and child intelligence quotient (IQ) is suggestive only (Chiu et al. 2016; Harris et al. 2015), we were not able to consider the potentially large benefit of RGGI in terms of improvement in child IQ. Decreased IQ in boys has been associated with gestational exposure to higher $PM_{2.5}$ levels (Chiu et al. 2016). Prenatal exposure to polycyclic aromatic hydrocarbons, a component of $PM_{2.5}$, has also been associated with lower child IQ (Perera et al. 2009). In addition, the association between PTB and IQ reduction, previously identified in the literature (for review, see Allotey et al. 2018; Bhutta et al. 2002; Kerr-Wilson et al. 2012), is not accounted for—thereby underestimating the impacts of PTB. A meta-analysis by Kerr-Wilson et al. (2012) estimated a decrement of 11.94 (95% confidence interval: 10.47, 13.42) IQ points among preterm children compared with children born at term. The loss of 1 IQ point has been estimated to result in a $17,815 loss of lifetime earnings per child (Gould 2009). Therefore, preventing the contribution of $PM_{2.5}$ exposure to PTB could have substantial economic benefits.

We note that the evidence with respect to $PM_{2.5}$ and ASD support a likely causal association. A highly cited systematic review and meta-analysis by Lam et al. (2016) has identified a number of studies on air pollution exposure during developmental periods that have found associations with ASD. The analysis by Lam et al. (2016) included 23 human studies published between 2006 and 2015, 9 of which assessed particulate matter (including PM_{10} and $PM_{2.5}$). The review found evidence for associations between prenatal exposure to $PM_{2.5}$ and ASD (Lam et al. 2016). Additional studies have been published since this review that have found positive associations between prenatal and/or early life $PM_{2.5}$ exposure and ASD (Kaufman et al. 2019; Jo et al. 2019; McGuinn et al. 2020).

Despite its limitations, the present analysis provides evidence of the importance of comprehensive assessments of child health benefits in analyses of the benefits of climate mitigation and air pollution emissions reduction policies. With respect to the distributional impacts, additional research is needed to refine and extend the overall benefits estimates provided here. Nevertheless, this analysis has estimated substantial benefits of RGGI for children's health.

Conclusion

Findings from the present assessment indicate that RGGI has provided considerable child health benefits to participating and neighboring states beyond those conventionally considered. Moreover, those health benefits are estimated to have significant economic value. Our assessment of the projected health co-benefits to children under RGGI can provide valuable support for the design and implementation of future programs to mitigate climate change targeting other sectors, including the transportation sector. Findings from this assessment also should encourage other states to join the program or initiate similar strategies of their own. In addition, our newly incorporated C-R functions and economic values for children's health end points into BenMAP are important additions to the existing program, which can be used widely. In this sense, the present study is generalizable and the methods can be used to quantify children's health and economic benefits under other climate change mitigation, air pollution control, and environmental programs.

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