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Impacts of the Regional Greenhouse Gas Initiative (RGGI) on Infant Mortality in the United States

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Keywords: regional greenhouse gas initiative (RGGI); carbon dioxide (CO2); neonatal mortality; infant mortality

Abstract

Objectives The Regional Greenhouse Gas Initiative (RGGI) is the first regulatory program to limit regional CO_2 emissions in the United States. Empirical evidence has shown the association of high concentrations of ambient air pollutants with an increased risk of morbidity and premature mortality. The purpose of this study was to examine the impacts of RGGI on death rates in infancy.

Design A quasi-experimental difference-in-differences design

Setting and Participants We estimated the impacts of RGGI on infant mortality from 2003 through 2014 in the United States (6 years before and after RGGI implementation). Our analytic models included state and year fixed effects in addition to a number of covariates.

Outcome measures Death rates in infancy: neonatal mortality rates (NMRs), deaths under 28 days as well as infant mortality rates (IMRs), deaths under 1 year

Results Implementation of RGGI was associated with significant decreases in overall NMRs (a reduction of 0.38/1,000 live births) and male NMRs (a reduction of 0.39/1,000 live births). However, RGGI did not have a significant effect on female NMRs. Similarly, overall IMRs and male IMRs decreased significantly by 0.31/1,000 live births and 0.53/1,000 live births, respectively, after implementation of RGGI while female IMRs were not significantly affected by RGGI.

Conclusions RGGI was associated with decreases in overall infant mortality and boy mortality through reducing air pollutant concentrations. Of note, this environmental policy did not significantly affect deaths in infant girls.

Strengths and limitations of this study

- This is the first study that examined the effects of the Regional Greenhouse Gas Initiative (RGGI) on infant death rates by sex.
- We investigated how the implementation of RGGI affected mortality outcomes such as neonatal mortality rates (NMRs) and infant mortality rates (IMRs) from 2003 through 2014 using a quasi-experimental difference-in-differences design.
- We included state and year fixed effects as well as a number of covariates in our analytic models.
- An assumption of the difference-in-differences approach should be met to produce reliable results.
- Because infant deaths in this study were all-cause mortality, our analyses were not granular enough to capture the reasons for deaths.

INTRODUCTION

The Regional Greenhouse Gas Initiative (RGGI) is the first mandatory cap-and-trade program designed to reduce greenhouse gas (GHG) emissions in the United States. Cap-and-trade refers to creating a limit or 'cap' on GHG emissions from various emission sources. The RGGI program limits carbon dioxide (CO_2) emissions, in particular, from the electric power sector, the largest source of CO_2 emissions for more than 40 years in the U.S. The RGGI program became effective in January 2009 in ten northeastern states. New Jersey originally participated in this program in 2009 but withdrew in 2011. Accordingly, electric power plants with 25 or more megawatts (MWs) capacity in the remaining nine states continue to participate in the RGGI program. As expected, CO_2 emissions have fallen considerably in these nine states since its implementation in 2009 [1-4].

Prior studies have consistently shown the association of high concentrations of ambient air pollutants with an increased risk of morbidity and premature mortality. For example, extensive evidence has shown that ambient air pollutants were positively associated with asthma, lung cancer, respiratory mortality, cardiovascular mortality, and total mortality [5-8]. Some studies examined the impact of air pollution focusing particularly on infant health given that air pollution can have negative effects on pregnant women, which can adversely affect the fetal immune system, even causing death [9-11]. Infants with weaker immune systems are more susceptible to dying from a wide range of causes [12]. Of interest, findings from these studies were compatible. One study found that regulations to reduce air pollution led to modest but statistically insignificant improvement in infant mortality in India [9] whereas other studies showed that infant mortality was significantly lowered following environmental regulations in Germany and China [10,11]. The impacts of air pollution on infant mortality might vary by country because of differences in medical care consumption and behaviors to avoid exposure to air pollution among countries [13].

In the U.S., some studies have shown that reductions in air pollution significantly decreased infant mortality [12,14,15]. These studies evaluated infant mortality in the 1990s or earlier. Recent U.S.-based studies regarding infant mortality have focused largely on its association with factors other than air pollution such as infants' demographics [16-18], state-level minimum wage laws [19], and Medicaid expansion [20]. The objective of this study was to investigate the impact of the environmental policy, RGGI, on infant mortality in recent years in the United States. Because some studies suggested that the effects of air pollution on health outcomes may be sex specific [21-23], we examined its impact also by sex.

METHODS

Infant mortality and RGGI

The main dependent variables are two state-level death rates in infancy: neonatal mortality rates (NMRs, deaths under 28 days) and infant mortality rates (IMRs, deaths under 1 year) from 2003 through 2014 (6 years before and after RGGI implementation in 2009). We obtained annual NMRs and IMRs from the National Vital Statistics System for this time period. U.S. states were categorized by whether they implemented the RGGI program (RGGI states) or not (non-RGGI states).

Covariates

We included a number of state-level covariates in our analyses to control for potential confounders. To adjust for economic performance and population size of the included states, we obtained regional Gross Domestic Product (GDP) and residential population data from the Federal Reserve Bank (Federal Reserve Economic Data, FRED) to include them as covariates in our model. To control for the characteristics of infants and mothers, we included total number of births, birth weight, black birth rate, and mother's education level (i.e., rate of high school graduate or higher), all of which were obtained from the Centers for Disease Control and Prevention Wide-ranging ONline Data for Epidemiologic Research (CDC WONDER) database. Finally, using data from the Henry J Kaiser Family Foundation (KFF) [24], we included the number of hospitals in each state.

However, mothers' education data were not available in some states. Accordingly, we excluded these states in our analysis: one RGGI state (Connecticut) and three non-RGGI states (Arizona, Illinois, and Tennessee). New Jersey was also excluded from the RGGI states because this state withdrew from the RGGI program in 2011, resulting in the inclusion of a total of 46 states in our analysis. Of these 46 states, eight states (Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont) were categorized as RGGI states.

Statistical Analysis

We investigated the impacts of RGGI on mortality outcomes by using a difference-in-differences approach. Specifically, we compared changes in mortality outcomes among RGGI states with those among non-RGGI states after the implementation of RGGI to assess how this implementation affected mortality outcomes such as NMRs and IMRs. To compare mortality changes over time, we used a multivariate regression model by controlling for a number of covariates such as regional GDP, residential population, total number of births, birth weight, black birth rate, mother's education level, and number of hospitals. A full set of year and state fixed effects were also included in our model to control for unobservable time invariant and state specific effects. An interaction term between RGGI status and time in our model captures the impacts of RGGI on mortality outcomes. Mortality outcomes were also examined by sex.

Thus, the model is specified as follows:

$$Y_{it} = \alpha + \beta_1 (PD*TD) + \beta_2 X_{it} + \gamma_i + \delta_t + \varepsilon_{it}$$

where Y_{it} is death rates in infancy in state i in year t, PD is a policy dummy variable that takes one for RGGI states and zero for non-RGGI states, TD is a time dummy variable that equals one for years 2009 or later and zero for years 2008 or earlier, X_{it} indicates control variables, γ_i is state fixed effect, and δ_t is time fixed effect. The coefficient β_1 represents the RGGI effects on infant mortality, capturing the difference in the changes in NMRs and IMRs before and after the environmental policy between RGGI states and non-RGGI states.

In addition, we performed sensitivity analysis by excluding data from the years 2008 and 2009 to eliminate any exogenous factors that could potentially reduce GHG emissions. Prior study has reported that the economic recession and moderate weather in the northeastern U.S. during 2008 and 2009 could lower economic activity and electricity demand, which might have resulted in lower GHG emissions [2].

To account for within-state serial correlation, we used state-clustered standard errors in our analyses. All analyses were conducted using STATA version 12 (Stata-Corp LP, College Station, TX).

Patient and Public Involvement

Neither patients nor public were involved in this study. Because this study used de-identified, aggregated, and publicly available secondary data, informed consent and ethical approval were not required.

RESULTS

Characteristics of RGGI states and non-RGGI states are presented in Table 1. No significant differences were observed between RGGI states and non-RGGI states in characteristics such as regional GDP, residential population, black birth rate, and mother's education levels. However, compared with non-RGGI states, RGGI states had both lower total number of births and number of hospitals although the average birth weight in RGGI states was higher.

Table 2 presents the difference-in-differences estimates of the RGGI's impact on mortality outcomes. Our results from an adjusted model show that implementation of RGGI was associated with significant decreases in overall NMRs (a reduction of 0.38/1,000 live births) and male NMRs (a reduction of 0.39/1,000 live births) in RGGI states. However, RGGI did not have a significant effect on female NMRs. Similarly, overall IMRs and male IMRs decreased significantly by 0.31/1,000 live births and 0.53/1,000 live births, respectively after implementation of RGGI while female IMRs was not significantly affected by RGGI. Full results obtained from the difference-in-differences regressions are available in supplementary Table 1.

These findings were not changed in our sensitivity analysis when data from the years 2008 and 2009 were excluded in the analysis (Table 3). That is, overall NMRs and male NMRs (0.50/1,000 live births and 0.56/1,000 live births, respectively) as well as overall IMRs and male IMRs (0.42/1,000 live births and 0.72/1,000 live births, respectively) were significantly reduced in RGGI states after the implementation of RGGI although mortality among female infants did not significantly changed.

DISCUSSION

RGGI, the first regulatory greenhouse gas emission trading scheme in the U.S., was implemented in 2009. The objective of this study was to examine whether its implementation affected public health, particularly infant death rates, since infant mortality has been widely accepted as a proxy for public health. Our results showed that implementation of RGGI was associated with a reduction in overall neonatal deaths and overall infant deaths. This could be explained by fuel switching trends observed in RGGI states. Previous studies have reported that RGGI implementation has encouraged fuel switching from coal to clean natural gas in electricity generation in the U.S. [2,3,25] Fossil fuels such as coals and petroleum are high carbon intensity sources which emit two times or more CO_2 than does natural gas. As such, total CO_2 emissions from power plants in RGGI states have dropped substantially. A decrease in air pollutants concentrations must have improved air quality in RGGI states, which most likely accounted for reduced overall infant death rates. Associations of air pollution with risk of premature mortality have been evidenced in a number of studies [7,8,10,11]. Indeed, our further analysis with CO_2 data in the 46 states also showed associations of an air pollutant (CO_2) with infant mortality (Change in overall NMRs per unit increase in CO_2: 0.007/1,000 live births, p = 0.003; change in overall IMRs per unit increase in CO_2: 0.009/1,000 live births, p = 0.019, see supplementary Table 2 for full results). Chay and Greenstone suggested air pollution's adverse effects on fetal development as a mechanism through which air pollution affects infant mortality [14,15].

Another finding of this study was the sex differences in the impact of RGGI on infant health. That is, male NMRs and male IMRs were significantly reduced after the implementation of RGGI while this environmental policy did not significantly affect deaths in female infants. This finding aligns with the Traffic-Related Air Pollution on Childhood Asthma (TRAPCA) study reporting different health responses in boys and girls aged 0-2 to air pollution [26]. The TRAPCA study showed stronger associations between air pollutants and nonspecific respiratory symptoms (e.g., cough without infection; nocturnal dry cough) among males than among females [26]. Greater susceptibility to diseases and higher mortality among boys have been explained by the differences in genetic and biological makeup between boys and girls. Female infants are known to have larger airways relative to body size [27], and their specific airway resistance is lower than in male infants [28]. However, studies of older children and adults often suggest stronger effects of air pollution among females. For older-aged children and adults, not only biological sex differences but also other social gender differences come into play in modifying the effects of air pollution. In general, social gender can affect the presence of exposures (e.g., exposure from using cosmetics or jewelry), the intensity of exposures (e.g., frequency of cooking), and co-exposures (e.g., diet or smoking). These social gender differences can change over the life course and do not exhibit predictable patterns. Therefore, these social gender differences aggregated with biological sex differences make gender effects more complicated, which might have led to large variations in the findings among prior studies for older-aged children and adults [22]. Regarding infants in this study and the TRAPCA study, observed modification was most likely attributable to biological sex differences. In other words, social gender differences were less likely to serve as an effect modifier in these two studies.

The impacts of implementation of RGGI on infant death rates were not changed when timeframe was varied in our sensitivity analysis. We excluded data from the years 2008 and 2009 in our sensitivity analysis to isolate the impact of RGGI on infant deaths while eliminating the effects of the economic recession and moderate weather during this time period. As noted earlier, the economic recession and moderate weather could have led to a reduction in GHG emissions, thereby affecting infant mortality. Findings in all sensitivity analysis were consistent with our base-case analysis indicating linkage between RGGI and infant mortality reduction (e.g., total NMRs and male NMRs as well as total IMRs and male IMRs).

To the best of our knowledge, this study represents the first attempt to examine infant health effects associated with a specific U.S. environmental regulation, RGGI. In particular, we examined the RGGI effects on infant health stratified by sex. Our study findings have important implications for environmental and public health policy. According to the World Health Organization (WHO), one out of every nine deaths at all ages directly resulted from air pollution in 2012, indicating air pollution as a large environmental health risk [29]. Annual global cost of health care related to pollution was estimated to be between $240 billion and $630 billion [30]. To cope with air pollution problems, the European Union has implemented the European Union Emission Trading Scheme (EU ETS), the world's first cap-and-trade program, to limit GHG emissions cost-effectively since 2005. Benefits of this program have emerged yielding significant reductions in GHG emissions in the EU [31,32]. Similarly, our findings show the beneficial effects of the U.S.'s cap-and-trade program to limit CO_2 emissions, which informs policymakers of the tangible public health benefits of RGGI. RGGI's experiences can encourage non-RGGI states to enhance their efforts to reduce CO_2 emissions or participate in the RGGI program, thereby broadening the RGGI market. This could lead to air quality improvements in more states, which can significantly benefit infant health. Alternatively, RGGI could be viewed as potential federal legislation.

Several limitations warrant discussion. First, an assumption behind the difference-in-differences approach is that without the implementation of RGGI, the non-RGGI states would have experienced a similar trend in infant deaths to the RGGI states (parallel trend assumption). However, this assumption could be violated if there is any unobserved policy change affecting infant health in non-RGGI states only. A violation of the parallel trend assumption would make our estimates biased. As such, we performed a test to check whether this assumption was met. Our test results of the pre-RGGI period showed no significantly different trends in infant mortality between RGGI states and non-RGGI states. While this trend might not persist in the post-RGGI period, it suggests that any bias from the violation of this assumption is likely to be small. Second, RGGI states have entered a second phase in which the existing cap level has been reduced to match their actual CO_2 emissions levels since 2014. Accordingly, the emission cap declines 2.5 percent each year between 2015 and 2020 in this new phase. Therefore, it is uncertain how differently the adjusted (reduced) emissions cap will impact electricity and, in turn, public health than the original emissions cap. A future follow-up study extending the timeframe may elucidate this point. Finally, infant deaths in this study were all-cause mortality rather than disease-specific mortality. Accordingly, our analyses were not granular enough to capture the reasons for deaths. Condition-specific mortality would provide information on which fetal organ systems are most affected by air pollution. However, despite this limitation, our study shows the comprehensive health effects in infants associated with air pollution.

In conclusion, the RGGI program started as a means to limit CO_2 emissions in January 2009 in the U.S. Although this program was originally designed to spur innovation in the clean energy economy, it also conferred significant benefits to infant health. Our study found that RGGI was associated with reductions in air pollutants, which in turn decreases infant mortality. This finding would be informative to policymakers. Future environmental and public health policy can be implemented toward expanding the benefits of RGGI. These implication is particularly noteworthy in the U.S. which still has a relatively high infant mortality compared with other developed peer countries [33].

CONTRIBUTORS:

J. Lee analyzed the data. Both J. Lee and T. Park conceptualized and designed the study, interpreted the results, and drafted and revised the article.

FUNDING:

All authors have nothing to declare. No funding has been received to conduct this study or prepare this manuscript.

COMPETING INTERESTS: None declared

PATIENCT CONSENT: Not required

ETHICS APPROVAL: Institutional review board approval was not required because this study used de-identified, aggregated, and publicly available secondary data.

DATA SHARING STATEMENT: No additional data available

Table 1. Characteristics of RGGI states vs. non-RGGI states in the US, 2003-2014

	All states	RGGI states	Non-RGGI states	*p*-value[a]
Regional GDP (Millions of USD), mean ± SD	265,475 ± 264,760	226,010 ± 152,246	273,784 ± 282,224	0.1081
Population (1,000 of person), mean ± SD	5,813 ± 6,950	4,602 ± 6,017	6,067 ± 7,111	0.0603
Number of birth, mean ± SD	78,237 ± 98,505	56,620 ± 77,033	82,788 ± 101,942	0.0179
Birth weight (grams), mean ± SD	3,277 ± 64	3,314 ± 50	3,269 ± 64	< 0.001
Black birth rate, %	15.69 ± 2.82	15.43 ± 2.43	15.74 ± 2.89	0.3304
Mother's education level, High school graduate or higher (%)	81.32 ± 7.53	82.06 ± 4.04	81.17 ± 6.94	0.2224
Number of hospitals, mean ± SD	97 ± 81	52 ± 57	106 ± 82	< 0.001

RGGI: regional greenhouse gas initiative

[a] t-tests (or Wilcoxon rank-sum tests) for continuous data, chi-squared tests for proportions in categories

Table 2. Impacts of RGGI on mortality outcomes in the US, 2003-2014

Outcomes			Change in Rate (SE)	p-value
Crude[a]	NMR, per 1,000 live births	Total	-0.423 (0.088)	< 0.001
		Males	-0.460 (0.153)	0.004
		Females	-0.234 (0.146)	0.116
	IMR, per 1,000 live births	Total	-0.496 (0.159)	0.003
		Males	-0.797 (0.231)	0.001
		Females	-0.360 (0.211)	0.095
Adjusted[b]	NMR, per 1,000 live births	Total	-0.378 (0.104)	0.001
		Males	-0.385 (0.168)	0.027
		Females	-0.196 (0.139)	0.164
	IMR, per 1,000 live births	Total	-0.314 (0.126)	0.017
		Males	-0.530 (0.174)	0.004
		Females	-0.161 (0.151)	0.289

[a] Adjusted for state and year fixed effects only

[b] Adjusted for state and year fixed effects, regional GDP, residential population, total number of births, birth weight, black birth rate, mother's education level, and number of hospitals

Table 3. Sensitivity analysis results: RGGI impacts on morality outcomes[a]

Variable	Change in NMRs, per 1,000 live births (SE)			Change in IMRs, per 1,000 live births (SE)		
	Total	Boys	Girls	Total	Boys	Girls
Regional GDP	-1.20e-06	-1.31e-06	-1.22e-06	-2.44e-06	-2.76e-06	-2.96e-06
	(1.10e-06)	(1.35e-06)	(9.33e-07)	(1.69e-06)	(2.20e-06)	(1.57e-06)
Population	-0.0002422	-0.0002437	-0.0002479*	-0.0003235	-0.0004695*	-0.0003676*
	(0.0001243)	(0.0001376)	(0.0001186)*	(0.0001784)	(0.0002272)*	(0.0001732)*
Number of birth	3.00e-06	4.75e-06	1.82e-06	1.96e-06	0.0000118	6.49e-06
	(5.10e-06)	(5.43e-06)	(5.79e-06)	(6.41e-06)	(9.67e-06)	(6.34e-06)
Birth weight	-0.0082725	-0.0039672	-0.0131509	-0.0130415	-0.0122741	-0.0208005
	(0.0056954)	(0.0051738)	(0.0071761)	(0.0085102)	(0.0097308)	(0.0113099)
Black birth rate	0.0113741	0.000601	0.0085723	0.0876092*	0.1161955	0.1352296***
	(0.0297199)	(0.0462012)	(0.0390364)	(0.0353495)*	(0.0610224)	(0.0337289)***
Mother's education level	-0.6961143	-1.328607	-0.2573584	-2.026255	-2.867125	-1.262401
	(0.9479541)	(1.279653)	(0.7988161)	(1.6679)	(2.18859)	(1.504969)
Number of hospital	-0.0120993	-0.0144852	-0.0074665	-0.009102	-0.0164292	-0.0127519
	(0.0075488)	(0.0088964)	(0.0079148)	(0.0089574)	(0.0135195)	(0.0107572)
Interaction term[b]	-0.4951883***	-0.558619***	-0.243341	-0.4198482*	-0.7152238***	-0.2223167
	(0.1210593)***	(0.155014)***	(0.1509518)	(0.1636079)*	(0.1921474)***	(0.1729693)

RGGI: regional greenhouse gas initiative; NMRs: neonatal mortality rates; IMRs: infant mortality rates
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$
[a] Excluding data from the years 2008 and 2009
[b] This interaction term between RGGI status and time captures the impacts of RGGI on mortality outcomes.

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Supplementary Table 1. Adjusted difference-in-differences (DID) estimators of RGGI impact on infant deaths

Variable	Change in NMRs, per 1,000 live births (SE)			Change in IMRs, per 1,000 live births (SE)		
	Total	Boys	Girls	Total	Boys	Girls
Regional GDP	-1.26e-06	-1.42e-06	-1.20e-06	-2.49e-06	-2.85e-06	-2.93e-06
	(1.08e-06)	(1.37e-06)	(8.70e-07)	(1.66e-06)	(2.21e-06)	(1.50e-06)
Population	-0.0002536	-0.0002598	-0.000251	-0.0003399	-0.0004918*	-0.0003738*
	(0.0001274)	(0.0001412)	(0.0001195)	(0.0001816)	(0.0002312)*	(0.0001741)*
Number of birth	1.93e-06	4.67e-06	-6.12e-08	1.92e-06	0.0000124	5.09e-06
	(4.63e-06)	(5.38e-06)	(4.96e-06)	(5.99e-06)	(9.81e-06)	(5.55e-06)
Birth Weight	-0.0076177	-0.0037701	-0.0114326	-0.0122273	-0.0116899	-0.0191533
	(0.0052942)	(0.0046785)	(0.0067851)	(0.0077142)	(0.0086235)	(0.0105127)
Black birth rate	0.0064637	-0.0107667	0.0099101	0.0772841*	0.0967207	0.1334212***
	(0.0242477)	(0.0347614)	(0.0338762)	(0.0300239)*	(0.051612)	(0.0290955)***
Mother's education level	-0.0068522	-0.0129052	-0.0025334	-0.018211	-0.026208	-0.0119060
	(0.0085526)	(0.0118166)	(0.0072852)	(0.0148736)	(0.0202634)	(0.0131637)
Number of hospital	-0.0124642	-0.0138966	-0.009093	-0.0100923	-0.016641	-0.0153282
	(0.0073727)	(0.0088915)	(0.0075518)	(0.0088321)	(0.0129295)	(0.0103395)
Interaction term[a]	***-0.3771778****	***-0.3845627****	***-0.1962053***	***-0.3144423****	***-0.530082*****	***-0.1614275***
	(0.1035355)*	***(0.1681352)****	***(0.1388334)***	***(0.1263745)****	***(0.1735499)*****	***(0.1505714)***

RGGI: regional greenhouse gas initiative; NMRs: neonatal mortality rates; IMRs: infant mortality rates
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$
[a] This interaction term between RGGI status and time captures the impacts of RGGI on mortality outcomes.

Supplementary Table 2. Impact of an air pollutant (CO_2) on infant deaths

Variable	Change in NMRs, per 1,000 live births (SE)			Change in IMRs, per 1,000 live births (SE)		
	Total	Boys	Girls	Total	Boys	Girls
CO_2	***0.0073489*****	***0.0094904****	***0.0049949***	***0.0089987****	***0.0112684****	***0.0060079***
	(0.0030021)**	***(0.0035972)****	***(0.0033248)***	***(0.0036889)****	***(0.0052512)****	***(0.0043243)***
Regional GDP	-1.48e-06	-1.64e-06	-1.30e-06	-2.66e-06	-3.16e-06	-3.01e-06*
	(1.13e-06)	(1.40e-06)	(8.81e-07)	(1.68e-06)	(2.28e-06)	(1.49e-06)*
Population	-0.0001791	-0.0001674	-0.0002043	-0.0002552	-0.0003797	-0.0003196
	(0.0001149)	(0.0001221)	(0.0001169)	(0.0001603)	(0.0002055)	(0.0001669)
Number of birth	-1.32e-06	2.58e-07	-2.41e-06	-2.29e-06	7.32e-06	2.20e-06
	(4.82e-06)	(6.01e-06)	(4.69e-06)	(6.82e-06)	(0.000011)	(5.80e-06)
Birth weight	-0.0073021	-0.0035871	-0.0115019	-0.0122349	-0.0113349	-0.0192953
	(0.0052751)	(0.0046352)	(0.0067637)	(0.0077008)	(0.0085938)	(0.0104703)
Black birth rate	0.0081531	-0.0104012	0.0093808	0.0754036*	0.0980182	0.1307669***
	(0.025777)	(0.0379529)	(0.0329269)	(0.0306248)*	(0.0543986)	(0.0284022)***
Mother's education level	-0.7003357	-1.241868	-0.2200329	-1.741112	-2.611714	-1.104435
	(0.9761654)	(1.3099)	(0.7962041)	(1.608477)	(2.200072)	(1.372992)
Number of hospital	-0.0068916	-0.0078965	-0.0060419	-0.0050128	-0.0086673	-0.0125169
	(0.0074591)	(0.0083925)	(0.0075057)	(0.0083519)	(0.0127257)	(0.0100353)

RGGI: regional greenhouse gas initiative; NMRs: neonatal mortality rates; IMRs: infant mortality rates
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

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Impacts of the Regional Greenhouse Gas Initiative (RGGI) on infant mortality: a quasi-experimental study in the United States, 2003–2014

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Keywords: regional greenhouse gas initiative (RGGI); carbon dioxide (CO2); neonatal mortality; infant mortality

Abstract

Objectives The Regional Greenhouse Gas Initiative (RGGI) is the first mandatory market-based regulatory program to limit regional CO_2 emissions in the United States. Empirical evidence has shown that high concentrations of ambient air pollutants such as CO_2 have been positively associated with an increased risk of morbidity (e.g., respiratory conditions including asthma and lung cancer) and premature mortality. The purpose of this study was to examine the impacts of RGGI on death rates in infancy.

Design A quasi-experimental difference-in-differences design

Setting and Participants We estimated the impacts of RGGI on infant mortality from 2003 through 2014 in the United States (6 years before and after RGGI implementation). Our analytic models included state and year fixed effects in addition to a number of covariates.

Outcome measures Death rates in infancy: neonatal mortality rates (NMRs), deaths under 28 days as well as infant mortality rates (IMRs), deaths under 1 year

Results Implementation of RGGI was associated with significant decreases in overall NMRs (a reduction of 0.41/1,000 live births) and male NMRs (a reduction of 0.43/1,000 live births). However, RGGI did not have a significant effect on female NMRs. Similarly, overall IMRs and male IMRs decreased significantly by 0.37/1,000 live births and 0.61/1,000 live births, respectively, after implementation of RGGI while female IMRs were not significantly affected by RGGI.

Conclusions RGGI was associated with decreases in overall infant mortality and boy mortality through reducing air pollutant concentrations. Of note, the impact of this environmental policy on infant girls was much smaller.

Strengths and limitations of this study

- This is the first study that examined the effects of the Regional Greenhouse Gas Initiative (RGGI) on infant death rates by sex.
- We investigated how the implementation of RGGI affected mortality outcomes such as neonatal mortality rates (NMRs) and infant mortality rates (IMRs) from 2003 through 2014 using a quasi-experimental difference-in-differences design.
- We included state and year fixed effects as well as a number of covariates in our analytic models.
- An assumption of the difference-in-differences approach should be met to produce reliable results.
- Because infant deaths in this study were all-cause mortality, our analyses were not granular enough to capture the reasons for deaths.

INTRODUCTION

The Regional Greenhouse Gas Initiative (RGGI) is the first mandatory cap-and-trade program designed to reduce greenhouse gas (GHG) emissions in the United States. Cap-and-trade refers to creating a limit or "cap" on GHG emissions from various emission sources. The RGGI program limits carbon dioxide (CO_2) emissions in particular from the electric power sector, the largest source of CO_2 emissions for more than 40 years in the U.S. The RGGI program is often referred to as a market-based CO_2 emission reduction program because, under this program, the marketplace determines the economically efficient solution for GHG emission reduction. The RGGI program became effective in January 2009 in ten northeastern states. New Jersey originally participated in this program in 2009, but withdrew in 2011. Accordingly, electric power plants with 25 or more megawatts (MWs) capacity in the remaining nine states continue to participate in the RGGI program. These nine states are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont. The RGGI program consists of four compliance periods, each of which lasts for three years (i.e., 2009–2011, 2012–2014, 2015–2017, and 2018–2020). During the first three-year compliance period (2009–2011), the emission cap was 188 million short tons of CO_2 (mtCO_2) per year, which was decreased to 165 mtCO_2 during the next period (2012–2013). The RGGI states then substantially reduced the emission cap from 165 mtCO_2 to 91 mtCO_2 in 2014. This cap has then gradually decreased by 2.5% each year from 2015 until 2020. As expected, CO_2 emissions have fallen considerably in these nine states since its implementation in 2009 [1-4].

Prior studies have consistently shown an association between high concentrations of ambient air pollutants and an increased risk of morbidity and premature mortality. For example, extensive evidence has shown that ambient air pollutants were positively associated with asthma, lung cancer, respiratory mortality, cardiovascular mortality, and total mortality [5-8]. Some studies examined the impact of air pollution particularly on infant mortality [9-11]; however, the findings from these studies are inconsistent. One study found that regulations to reduce air pollution led to modest but statistically insignificant improvement in infant mortality in India [9] whereas other studies showed that infant mortality was significantly lowered following environmental regulations in Germany and China [10,11]. The variations in the findings across studies might be driven by the different strengths of the relationships between air pollution and infant mortality among the countries.

In the U.S., some studies have shown that reductions in air pollution significantly decreased infant mortality [12-14]. These studies evaluated infant mortality in the 1990s or earlier. Recent U.S.-based studies regarding infant mortality have focused largely on its association with factors other than air pollution such as infants' demographics [15-17], state-level minimum wage laws [18], and Medicaid expansion [19]. The objective of this study was to investigate the impact of the environmental policy, RGGI, on infant mortality in recent years in the United States. Because some studies suggested that the effects of air pollution on health outcomes may be sex-specific [20-22], we examined its impact also by sex.

METHODS

Infant Mortality and RGGI

The main dependent variables are two state-level death rates in infancy: the neonatal mortality rate (NMR, deaths under 28 days) and infant mortality rate (IMR, deaths under 1 year) from 2003 through 2014 (6 years, respectively, before and after RGGI implementation in 2009). We obtained the annual NMRs and IMRs from the National Vital Statistics System for this time period [23]. U.S. states were categorized by whether they implemented the

RGGI program (RGGI states) or not (non-RGGI states).

Covariates

We included a number of state-level covariates in our analyses to control for potential confounders. To adjust for economic performance, population size, and household financial status of the included states, we obtained total Gross Domestic Product (GDP), residential population, and the median household income data from the Federal Reserve Bank (Federal Reserve Economic Data, FRED [24]) to include them as covariates in our model. To control for the characteristics of infants and mothers, we included total number of births, birth weight, birth rate of black babies, and mother's education level (i.e., rate of high school graduate or higher), all of which were obtained from the Centers for Disease Control and Prevention Wide-ranging ONline Data for Epidemiologic Research (CDC WONDER) database [25]. Furthermore, using data from the Henry J. Kaiser Family Foundation (KFF) [26], we included the number of hospitals in each state. Finally, we included the average temperatures of each state obtained from the National Oceanic and Atmospheric Administration [27].

However, mothers' education data were not available in some states. Accordingly, we excluded these states in our analysis: one RGGI state (Connecticut) and three non-RGGI states (Arizona, Illinois, and Tennessee). New Jersey was also excluded from the RGGI states because this state withdrew from the RGGI program in 2011; thus, our analysis included 46 states. Of these 46 states, eight states (Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont) were categorized as RGGI states.

Statistical Analysis

We investigated the impacts of RGGI on mortality outcomes by using a quasi-experimental difference-in-differences (DID) approach. The DID method is a useful tool to evaluate treatment effects by comparing the pre- and post-treatment differences in an outcome between a treatment group and a control group. This analytic method relies on the assumption that in the absence of the treatment, the average outcome for a treatment group would follow similar trends over time as the average outcome for a control group. Therefore, the treatment effect is estimated by comparing the average change in the outcome over time for the treatment group with the average change over time for the control group. In this study, we compared changes in mortality outcomes among RGGI states (treatment group) with those among non-RGGI states (control group) after the implementation of RGGI to assess how this implementation affected mortality outcomes such as NMRs and IMRs. To compare mortality changes over time, we used a multivariate regression model by controlling for a number of covariates such as GDP, residential population, total number of births, birth weight, birth rate of black babies, mother's education level, and number of hospitals. A full set of year and state fixed effects were also included in our model to control for unobservable time invariant and state-specific effects. An interaction term between RGGI status and time in our model captures the impacts of RGGI on mortality outcomes. Mortality outcomes were also examined by sex.

Thus, the DID model in this study is specified as follows:

$$Y_{it} = \alpha + \beta_1 (PD*TD) + \beta_2 X_{it} + \gamma_i + \delta_t + \varepsilon_{it}$$

where Y_{it} is death rate in infancy in state i in year t, PD is a policy dummy variable that takes one for RGGI states and zero for non-RGGI states, TD is a time dummy variable that equals one for years 2009 or later and zero for years 2008 or earlier, X_{it} indicates control variables, γ_i is state fixed effect, and δ_t is time fixed effect. The coefficient β_1 represents the RGGI effects on infant mortality, capturing the difference in the changes in NMRs and IMRs before and after the environmental policy between RGGI states and non-RGGI states.

In addition, we performed a sensitivity analysis by excluding data from the years 2008 and 2009 to eliminate any exogenous factors that could potentially reduce GHG emissions. A prior study reported that the economic recession and moderate weather in the northeastern U.S. during 2008 and 2009 could lower economic activity and electricity demand, which might have resulted in lower GHG emissions [2].

To account for within-state serial correlation, we used state-clustered standard errors in our analyses. All analyses were conducted using STATA version 12 (Stata-Corp LP, College Station, TX).

Patient and Public Involvement

Neither patients nor public were involved in this study. Because this study used de-identified, aggregated, and publicly available secondary data, informed consent and ethical approval were not required.

RESULTS

Characteristics of RGGI states and non-RGGI states are presented in Table 1. Compared with non-RGGI states, RGGI states had lower total number of births, number of hospitals, and average temperatures although the level of the median household income and the average birth weight in RGGI states were higher. However, no significant differences were observed between RGGI states and non-RGGI states in characteristics such as GDP, residential population, birth rate of black babies, and mother's education levels. In addition, the sex ratios of newborn males to newborn females were also similar between RGGI states and non-RGGI states before RGGI implementation (1.051 and 1.050, respectively) and after RGGI implementation (1.053 and 1.049, respectively) (data not shown in Table 1).

Figure 1 shows a trend in the observed overall NMRs and overall IMRs over time. Prior to RGGI implementation (2003–2008), changes in overall NMRs were –0.23 (= 4.38–4.61) per 1,000 live births and –0.38 (= 4.17–4.55) per 1,000 live births in non-RGGI states and RGGI states, respectively. Accordingly, RGGI states had a larger change in overall NMRs during 2003–2008 (difference in NMR changes between RGGI states and non-RGGI states during 2003–2008 = 0.15 per 1,000 live births). After RGGI implementation (2009–2014), changes in overall NMRs were –0.13 per 1,000 live births and –0.59 per 1,000 live births in non-RGGI states and RGGI states, respectively. Therefore, we could observe a much larger decrease in overall NMRs in RGGI states compared with non-RGGI states after RGGI implementation. The difference in NMR decreases between RGGI states and non-RGGI states during 2009–2014 (0.46 per 1,000 live births) was about three times higher than that before RGGI implementation (0.15 per 1,000 live births). Similarly, the decrease in overall IMRs among RGGI states was larger than that among non-RGGI states after RGGI implementation.

Table 2 presents the DID estimates of the RGGI's impact on mortality outcomes. As noted earlier, an interaction term in the adjusted DID model captures the effect of RGGI on infant death rates in RGGI states compared with its effect in non-RGGI states. Our results from an adjusted DID model show that implementation of RGGI was associated with significant decreases in overall NMRs (a reduction of 0.41/1,000 live births) and male NMRs (a reduction of 0.43/1,000 live births) in RGGI states ($p < 0.001$ and $p = 0.016$, respectively). However, RGGI did not have a significant effect on female NMRs ($p = 0.086$). Similarly, overall IMRs and male IMRs decreased significantly by 0.37/1,000 live births and 0.61/1,000 live births, respectively, after implementation of RGGI ($p = 0.003$ and $p = 0.001$, respectively) while female IMRs were not significantly affected by RGGI (p = 0.068). The full results obtained from the DID regressions are available in supplementary Table 1.

These findings were not substantially changed in our sensitivity analysis when data from the years 2008 and 2009 were excluded in the analysis (Table 3). That is, overall NMRs and male NMRs (0.53/1,000 live births and 0.62/1,000 live births, respectively) as well as overall IMRs and male IMRs (0.51/1,000 live births and 0.85/1,000 live births, respectively) were significantly reduced in RGGI states after the implementation of RGGI. However, female IMRs became significant with a reduction of 0.35/1,000 live births in the sensitivity analysis.

After verifying significant decreases in infant mortality outcomes among RGGI states during 2009–2014, we conducted further analyses to examine the association between an air pollutant (CO_2) and infant mortality. Our results indicate that the concentration of atmospheric CO_2 was positively associated with infant mortality (change in overall NMRs per unit increase in CO_2: 0.007/1,000 live births, p = 0.016; change in overall IMRs per unit increase in CO_2: 0.009/1,000 live births, p = 0.023, see supplementary Table 2 for full results).

DISCUSSION

RGGI, the first market-based regulatory greenhouse gas emission trading scheme in the U.S., was implemented in 2009. The objective of this study was to examine whether its implementation affected public health, particularly infant death rates, since infant mortality has been widely accepted as a proxy for public health. Our results showed that the implementation of RGGI was associated with a reduction in overall neonatal deaths and overall infant deaths. This could be explained by fuel switching trends observed in RGGI states. Previous studies have reported that RGGI implementation has encouraged fuel switching from coal to clean natural gas in electricity generation in the U.S. [2,3,28] Fossil fuels such as coal and petroleum are high carbon intensity sources which emit two times or more CO_2 than does natural gas. As such, total CO_2 emissions from power plants in RGGI states have dropped substantially. A decrease in air pollutant (CO_2) concentrations in RGGI states might be associated with the reduced overall infant death rates in these states. Associations of air pollution with risk of premature mortality have been evidenced in a number of studies [7,8,10,11]. Similarly, our further analyses also showed that overall NMRs and IMRs increased as the CO_2 level increased. Air pollution's adverse effects on fetal development were suggested by Chay and Greenstone as a mechanism through which air pollution affects infant mortality [13,14].

Another finding of this study was the differences in the impact of RGGI on the infant health of males and females. That is, male NMRs and male IMRs were significantly reduced after the implementation of RGGI while this environmental policy did not significantly affect deaths in female infants. This finding aligns with the Traffic-Related Air Pollution on Childhood Asthma (TRAPCA) study reporting different health responses in boys and girls aged 0–2 to air pollution [29]. The TRAPCA study showed stronger associations between air pollutants and non-specific respiratory symptoms (e.g., cough without infection; nocturnal dry cough) among males than among females [29]. Greater susceptibility to diseases and higher mortality among boys are used to explain by the differences in genetic and biological makeup between boys and girls. Female infants are known to have larger airways relative to body size [30] and their specific airway resistance is lower than in male infants [31]. However, studies of older children and adults often suggest stronger effects of air pollution among females. For older-aged children and adults, not only biological sex differences but also other social gender differences come into play in modifying the effects of air pollution.

In general, social gender can affect the presence of exposures (e.g., exposure from using cosmetics or jewelry), the intensity of exposures (e.g., frequency of cooking), and co-exposures (e.g., diet or smoking). These social gender differences can change over the life course and do not exhibit predictable patterns. Therefore, these social gender differences aggregated with biological sex differences make gender effects more complicated, which might have led to large variations in the findings among prior studies for older-aged children and adults [21]. Regarding infants in this study and the TRAPCA study, observed modification was most likely attributable to biological sex differences. In other words, social gender differences were less likely to serve as an effect modifier in these two studies.

The impacts of implementation of RGGI on infant death rates were not changed substantially when the timeframe was varied in our sensitivity analysis. We excluded data from the years 2008 and 2009 in our sensitivity analysis to isolate the impact of RGGI on infant deaths while eliminating the effects of the economic recession and the moderate weather experienced during this time period. As noted earlier, the economic recession and moderate weather could have led to a reduction in GHG emissions, thereby affecting infant mortality. Findings in the sensitivity analyses still indicated a linkage between RGGI and infant mortality reduction (e.g., total NMRs and male NMRs as well as total IMRs and male IMRs). Notably, female IMRs also reduced after the RGGI implementation although its impacts on female IMRs were much smaller than those on male IMRs.

To the best of our knowledge, this study represents the first attempt to examine infant health effects associated with a specific U.S. environmental regulation, RGGI. In particular, we examined the RGGI effects on infant health stratified by sex. Our study findings have important implications for environmental and public health policy. According to the World Health Organization, one out of every nine deaths at all ages directly resulted from air pollution in 2012, indicating air pollution as a large environmental health risk [32]. The annual global cost of health care related to pollution was estimated to be between $240 billion and $630 billion [33]. To cope with air pollution problems, the European Union implemented the European Union Emission Trading Scheme (EU ETS) in 2005, which is the world's first cap-and-trade program. Benefits of this program have emerged yielding significant reductions in GHG emissions in the EU [34,35]. Similarly, our findings show the beneficial effects of the U.S.'s cap-and-trade program to limit CO_2 emissions, which informs policymakers of the tangible public health benefits of RGGI. RGGI's experiences can encourage non-RGGI states to enhance their efforts to reduce CO_2 emissions or participate in the RGGI program, thereby broadening the RGGI market. This could lead to air quality improvements in more states, which can significantly benefit infant health. Alternatively, RGGI could be viewed as potential federal legislation.

Several limitations warrant discussion. First, an assumption behind the DID approach is that without the implementation of RGGI, the non-RGGI states would have experienced a similar trend in infant deaths to the RGGI states (parallel trend assumption). However, this assumption could be violated if there is any unobserved policy change affecting infant health in non-RGGI states only. A violation of the parallel trend assumption would make our estimates biased. As such, we performed a test to check whether this assumption was met. Our test results of the pre-RGGI period showed no significantly different trends in infant mortality between RGGI states and non-RGGI states. While this trend might not persist in the post-RGGI period, it suggests that any bias from the violation of this assumption is likely to be small. Second, RGGI states have entered a second phase in which the existing cap level has been reduced to match their actual CO_2 emissions levels since 2014. Accordingly, the emission cap declines 2.5 percent each year between 2015 and 2020 in this new phase.

Therefore, it is uncertain how differently the adjusted (reduced) emissions cap will impact infant mortality than the original emissions cap. A future follow-up study extending the timeframe may elucidate this point. Likewise, our study findings may not be generalizable to a greenhouse gas reduction policy outside the U.S. Moreover, infant deaths in this study were all-cause mortality rather than disease-specific mortality. Accordingly, our analyses were not granular enough to capture the reasons for deaths. Condition-specific mortality would provide information on which fetal organ systems are most affected by air pollution. However, despite this limitation, our study shows the comprehensive health effects in infants associated with air pollution. Finally, residual confounding by unmeasured factors might be possible, which is the limitation inherent in any observational studies. The study findings could be biased to the extent unmeasured confounders affect the association of RGGI implementation with infant mortality.

In conclusion, the RGGI program started as a means to limit CO_2 emissions in January 2009 in the U.S. Although this program was originally designed to spur innovation in the clean energy economy, it also conferred significant benefits to infant health. Our study found that RGGI was associated with decreases in infant mortality. This finding would be informative to policymakers. Future environmental and public health policy can be implemented toward expanding the benefits of RGGI.

CONTRIBUTORS:

J. Lee analyzed the data. Both J. Lee and T. Park conceptualized and designed the study, interpreted the results, and drafted and revised the article.

FUNDING:

All authors have nothing to declare. No funding has been received to conduct this study or prepare this manuscript.

COMPETING INTERESTS: None declared

PATIENCT CONSENT: Not required

ETHICS APPROVAL: Institutional review board approval was not required because this study used de-identified, aggregated, and publicly available secondary data.

DATA SHARING STATEMENT: No additional data available

Table 1. Characteristics of RGGI states vs. non-RGGI states in the US, 2003–2014

	All states	RGGI states	Non-RGGI states	p-value[a]
GDP (Millions of USD), mean ± SD	275,019 ± 363,987	259,637 ± 365,497	278,087 ± 362,357	0.6509
Population (1,000 of person), mean ± SD	5,813 ± 6,950	4,602 ± 6,017	6,067 ± 7,111	0.0603
Median household income (USD), mean ± SD	57,057 ± 8,560	63,801 ± 7,809	55,637 ± 8,024	< 0.001
Number of birth, mean ± SD	78,237 ± 98,505	56,620 ± 77,033	82,788 ± 101,942	0.0179
Birth weight (grams), mean ± SD	3,277 ± 64	3,314 ± 50	3,269 ± 64	< 0.001
Birth rate of black babies, %	15.69 ± 2.82	15.43 ± 2.43	15.74 ± 2.89	0.3304
Mother's education level, High school graduate or higher (%)	81.32 ± 7.53	82.06 ± 4.04	81.17 ± 6.94	0.2224
Number of hospitals, mean ± SD	97 ± 81	52 ± 57	106 ± 82	< 0.001
Average temperature (°F), mean ± SD	52.46 ± 9.36	48.33 ± 5.24	53.33 ± 9.80	< 0.001

RGGI: regional greenhouse gas initiative
[a] t-tests (or Wilcoxon rank-sum tests) for continuous data, chi-squared tests for proportions in categories

Table 2. Impacts of RGGI on mortality outcomes in the US, 2003–2014

	Outcomes		Change in Rate (SE)	p-value
Crude[a]	NMR, per 1,000 live births	Total	-0.423 (0.088)	< 0.001
		Males	-0.460 (0.153)	0.004
		Females	-0.234 (0.146)	0.116
	IMR, per 1,000 live births	Total	-0.496 (0.159)	0.003
		Males	-0.797 (0.231)	0.001
		Females	-0.360 (0.211)	0.095
Adjusted[b]	NMR, per 1,000 live births	Total	-0.405 (0.091)	< 0.001
		Males	-0.425 (0.170)	0.016
		Females	-0.215 (0.123)	0.086
	IMR, per 1,000 live births	Total	-0.370 (0.118)	0.003
		Males	-0.608 (0.170)	0.001
		Females	-0.242 (0.129)	0.068

[a] Adjusted for state and year fixed effects only

[b] Adjusted for state and year fixed effects, GDP, residential population, total number of births, birth weight, birth rate of black babies, mother's education level, number of hospitals, median household income, and average temperature

Table 3. Sensitivity analysis results: RGGI impacts on morality outcomes[a]

Variable	Change in NMRs, per 1,000 live births (SE)			Change in IMRs, per 1,000 live births (SE)		
	Total	Boys	Girls	Total	Boys	Girls
GDP	-1.86e-06	-1.91e-06	-2.09e-06	-3.02e-06	-2.53e-06	-2.71e-06
	(1.30e-06)	(1.34e-06)	(1.45e-06)	(1.75e-06)	(2.17e-06)	(2.05e-06)
Population	-0.0000259	-0.0000226	-0.0000220	7.01e-06	-0.0002216	-0.0001042
	(0.0002178)	(0.0002362)	(0.0002213)	(0.0002871)	(0.0003684)	(0.0002940)
Median household income	-7.70e-06	-1.32e-06	-2.75e-06	-3.42e-06	-3.23e-06	0.0000117
	(0.0000165)	(0.0000188)	(0.0000191)	(0.0000241)	(0.0000315)	(0.0000282)
Number of birth	3.45e-06	5.94e-06	1.32e-06	1.34e-06	0.0000110	3.89e-06
	(5.15e-06)	(5.69e-06)	(5.62e-06)	(7.02e-06)	(0.0000102)	(7.08e-06)
Birth weight	-0.0081901	-0.0035003	-0.0133304	-0.0125448	-0.0109829	-0.0195128
	(0.0057610)	(0.0051013)	(0.0076550)	(0.0089260)	(0.0100007)	(0.0123177)
Birth rate of black babies	0.0112633	0.0027859	0.0045914	0.0804308*	0.1073290	0.1170497**
	(0.0285210)	(0.0447368)	(0.0385191)	(0.0368247)*	(0.0645677)	(0.0333728)**
Mother's education level	-0.0074075	-0.0137847	-0.0022304	-0.0210392	-0.0302151	-0.0128773
	(0.0112689)	(0.0147682)	(0.0095342)	(0.0200455)	(0.0252871)	(0.0180780)
Number of hospital	-0.0226784*	-0.0262978*	-0.0182374	-0.0266599*	-0.0330336	-0.0293663*
	(0.0093494)*	(0.0100346)*	(0.0102170)	(0.0120942)*	(0.0175839)	(0.0139495)*
Average temperature	0.0117115	0.0215859	0.0125384	0.0327286	0.0485751	0.0625248
	(0.0197077)	(0.0255102)	(0.0238854)	(0.0289116)	(0.0372411)	(0.0396741)
Interaction term[b]	-0.5326649***	-0.6170827***	-0.2684320	-0.5085975**	-0.8462957***	-0.3538008*
	(0.1075000)***	(0.1519119)***	(0.1350443)	(0.1583920)**	(0.1865184)***	(0.1506759)*

RGGI: regional greenhouse gas initiative; NMRs: neonatal mortality rates; IMRs: infant mortality rates

**p* < 0.05, ***p* < 0.01, ****p* < 0.001

[a] Excluding data from the years 2008 and 2009

[b] This interaction term between RGGI status and time captures the impacts of RGGI on mortality outcomes.

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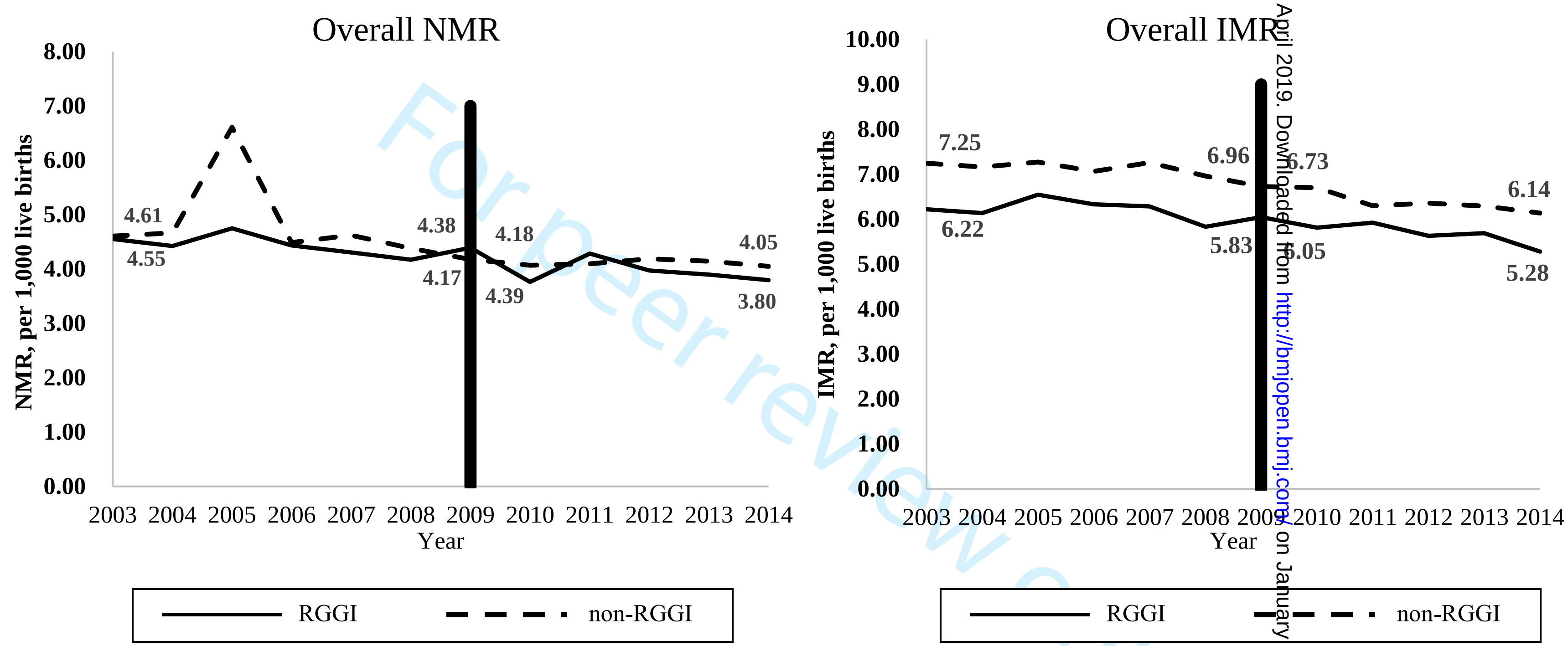
Figure 1. Observed (a) overall NMRs and (b) overall IMRs in RGGI states and non-RGGI states in the US, 2003–2014

(a) (b)



NMR: neonatal mortality rate; IMR: infant mortality rate; RGGI: regional greenhouse gas initiative

Supplementary Table 1. Adjusted difference-in-differences (DID) estimators of RGGI impact on infant deaths

Variable	Change in NMRs, per 1,000 live births (SE)			Change in IMRs, per 1,000 live births (SE)		
	Total	Boys	Girls	Total	Boys	Girls
GDP	-1.88e-06 (1.25e-06)	-2.00e-06 (1.28e-06)	-1.97e-06 (1.39e-06)	-2.91e-06 (1.65e-06)	-2.79e-06 (1.99e-06)	-2.61e-06 (1.93e-06)
Population	-0.0000360 (0.0002067)	-0.0000299 (0.0002216)	-0.0000188 (0.0002071)	-0.0000263 (0.0002662)	-0.0002092 (0.0003427)	-0.0001206 (0.0002697)
Median household income	-5.85e-06 (0.0000141)	-8.64e-06 (0.0000172)	-4.58e-07 (0.0000157)	-1.35e-06 (0.0000214)	4.98e-07 (0.0000296)	9.99e-06 (0.0000238)
Number of birth	2.78e-06 (4.68e-06)	5.97e-06 (5.66e-06)	1.92e-07 (4.85e-06)	2.03e-06 (6.44e-06)	0.0000123 (0.0000103)	3.95e-06 (6.05e-06)
Birth Weight	-0.0076359 (0.0052305)	-0.0035722 (0.0045584)	-0.0116215 (0.0069459)	-0.0122315 (0.0078172)	-0.0113665 (0.0086324)	-0.0187593 (0.0109595)
Birth rate of black babies	0.0063794 (0.0238573)	-0.0096344 (0.0353815)	0.0077642 (0.0334679)	0.0716882* (0.0325216)*	0.0893118 (0.0574333)	0.1210886*** (0.0289431)***
Mother's education level	-0.0071810 (0.0103181)	-0.0132788 (0.0138172)	-0.0021547 (0.0087753)	-0.0195957 (0.0183909)	-0.0280922 (0.0239215)	-0.0132134 (0.0166749)
Number of hospital	-0.0219685* (0.0086807)*	-0.0244326* (0.0092209)*	-0.0183177 (0.0097582)	-0.0247253* (0.0113998)*	-0.0311929 (0.0160545)	-0.0283967 (0.0133996)
Average temperature	0.0174274 (0.0150550)	0.0272269 (0.0210809)	0.0194400 (0.0169550)	0.0266512 (0.0176760)	0.0386144 (0.0280729)	0.0509284 (0.0259600)
Interaction term[a]	***-0.4052746****** ***(0.0916352)******	***-0.4250920**** ***(0.1698959)****	***-0.2150693*** ***(0.1225956)***	***-0.3704602***** ***(0.1179390)*****	***-0.6083323***** ***(0.1696649)*****	***-0.2418583*** ***(0.1294273)***

RGGI: regional greenhouse gas initiative; NMRs: neonatal mortality rates; IMRs: infant mortality rates
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$
[a] This interaction term between RGGI status and time captures the impacts of RGGI on mortality outcomes.

Supplementary Table 2. Impact of an air pollutant (CO_2) on infant deaths

Variable	Change in NMRs, per 1,000 live births (SE)			Change in IMRs, per 1,000 live births (SE)		
	Total	Boys	Girls	Total	Boys	Girls
CO_2	***0.0073101****	***0.0097754*****	***0.0046792***	***0.0087438****	***0.0110848****	***0.0056487***
	(0.0029335)*	***(0.0034832)*****	***(0.0033975)***	***(0.0037278)****	***(0.0051819)****	***(0.0044528)***
GDP	-2.08e-06	-2.13e-06	-2.06e-06	-3.02e-06*	-3.08e-06	-2.68e-06
	(1.15e-06)	(1.10e-06)	(1.31e-06)	(1.50e-06)*	(1.77e-06)	(1.84e-06)
Population	0.0000573	0.0000755	0.0000336	0.0000658	-0.0000687	-0.0000607
	(0.0002021)	(0.0002144)	(0.0002054)	(0.0002579)	(0.0003335)	(0.0002709)
Median household income	-6.94e-06	-0.0000106	-8.30e-07	-3.18e-06	-1.18e-06	9.09e-06
	(0.0000144)	(0.0000171)	(0.0000160)	(0.0000218)	(0.0000297)	(0.0000243)
Number of birth	-4.27e-07	1.57e-06	-1.99e-06	-1.87e-06	7.40e-06	1.40e-06
	(5.15e-06)	(6.69e-06)	(4.63e-06)	(7.61e-06)	(0.0000120)	(6.30e-06)
Birth weight	-0.0072781	-0.0032641	-0.0116317	-0.0120309	-0.0108363	-0.0186375
	(0.0051858)	(0.0044564)	(0.0069323)	(0.0077799)	(0.0085672)	(0.0109247)
Birth rate of black babies	0.0087439	-0.0080372	0.0080809	0.0719989*	0.0927604	0.1210849***
	(0.0260100)	(0.0391740)	(0.0327923)	(0.0335050)*	(0.0604250)	(0.0285270)***
Mother's education level	-0.0081373	-0.0137028	-0.0023198	-0.0199148	-0.0294975	-0.0133894
	(0.0117144)	(0.0152520)	(0.0094808)	(0.0196440)	(0.0259741)	(0.0173335)
Number of hospital	-0.0171739*	-0.0188265*	-0.0155750	-0.0198103	-0.0239671	-0.0251878
	(0.0084390)*	(0.0088341)*	(0.0094244)	(0.0108497)	(0.0153916)	(0.0128164)
Average temperature	0.0125618	0.0234299	0.0176772	0.0229965	0.0313541	0.0489418
	(0.0155256)	(0.0206881)	(0.0171763)	(0.0173919)	(0.0273600)	(0.0260103)

RGGI: regional greenhouse gas initiative; NMRs: neonatal mortality rates; IMRs: infant mortality rates

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

STROBE Statement—checklist of items that should be included in reports of observational studies[a]

	Item No	Recommendation	Yes	
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	√	See the title and the abstract.
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	√	See the abstract.
Background/ rationale	2	Explain the scientific background and rationale for the investigation being reported	√	See page 4, line 2 to page 5, line 13.
Objectives	3	State specific objectives, including any prespecified hypotheses	√	See page 5, lines 13–16.
Study design	4	Present key elements of study design early in the paper	√	See page 6, line 24 to page 7, line 10.
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	Not Applicable[b]	
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	Not Applicable[b]	
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case		
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	√	See page 5, line 19 to page 6, line 21.
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	√	See page 5, line 19 to page 6, line 21.
Bias	9	Describe any efforts to address potential sources of bias	√	See page 13, lines 12–21.
Study size	10	Explain how the study size was arrived at	Not Applicable[c]	
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	√	See page 6, lines 4–15.
Statistical	12	(*a*) Describe all statistical methods, including those used to control for confounding	√	See page 6, line 24 to

methods				page 8, line 9.
		(*b*) Describe any methods used to examine subgroups and interactions	√	See page 7, lines 16–17.
		(*c*) Explain how missing data were addressed	√	See page 6, lines 16-18.
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	Not Applicable[b]	
		(*e*) Describe any sensitivity analyses	√	See page 8, lines 2–6.
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	Not Applicable[b]	
		(b) Give reasons for non-participation at each stage		
		(c) Consider use of a flow diagram		
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	Not Applicable[b]	
		(b) Indicate number of participants with missing data for each variable of interest		
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)		
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	Not Applicable[b]	
		Case-control study—Report numbers in each exposure category, or summary measures of exposure		
		Cross-sectional study—Report numbers of outcome events or summary measures		
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	√	See Table 2.
		(*b*) Report category boundaries when continuous variables were categorized	√	See page 6, lines 10–11.
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	√	See page 9, lines 2–13.
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	√	See page 9, line 16 to page 10, line 8.
Discussion				
Key results	18	Summarise key results with reference to study objectives	√	See page 10, lines 20–23.
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	√	See page 13, line 12 to page 14, line 11.
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	√	See page 10, line 23 to page 12, line 18.

Generalisability	21	Discuss the generalisability (external validity) of the study results	√	See page 13, line 21 to page 14, line 3.
Other information				
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	√	See page 14, lines 23–25.

[a] The STROBE checklist was adopted from von Elm et al.'s study (von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP, STROBE Initiative. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *J Clin Epidemiol.* 2008;61(4):344-349).

[b] In this study, there is no individual study participant because the U.S. states serve as the unit of analysis. Accordingly, this study is not a cohort, case-control, or cross-sectional study.

[c] This study does not use primary data where formal, a priori calculation of sample size is required according to the STROBE statements guidelines.