THE ASSOCIATION BETWEEN REDUCTION IN $PM_{2.5}$ AND IMPROVEMENT IN CARDIOVASCULAR MORTALITY RATES

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ABSTRACT

Anne E. Corrigan: The Association between Reduction in $PM_{2.5}$ and Improvement in Cardiovascular Mortality Rates
(Under the direction of J. Jason West and Ana G. Rappold)

We examined the association between county-level change in $PM_{2.5}$ and change in cardiovascular mortality rate before and after implementation of the 1997 annual $PM_{2.5}$ National Ambient Air Quality Standards. We examined how the association varied between counties stratified by attainment designation and by design values used in the designation process to characterize air quality. We used linear regression and difference-in-difference models, adjusted for sociodemographic confounders.

Across 619 counties in the study, there were 1.10 (95% CI 0.37, 1.82) fewer deaths per year per 100,000 people per 1 $\mu g/m^3$ $PM_{2.5}$ decrease. Improvements in air quality and morality rates were greater in nonattainment counties and in the counties with the highest design values, while attainment counties and those with the lowest design values had greater decrease in mortality rate per unit decrease in $PM_{2.5}$; however, the differences between estimates changes in mortality rates were not statistically significant

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

AMR	Age-adjusted Mortality Rate
CAA	Clean Air Act
COPD	Chronic obstructive pulmonary disease
C-R	Concentration-Response
DV	Design Value
EPA	Environmental Protection Agency
FIPS	Federal Information Processing Standard
IQR	Interquartile range
MSA	Metropolitan Statistical Area
NAAQS	National Ambient Air Quality Standards
NCHS	National Center for Health Statistics
SES	Socioeconomic Status

CHAPTER 1: INTRODUCTION

Various provisions of the Clean Air Act (CAA) have driven the improvement of air quality across U.S. communities since its enactment in 1970 (EPA 2015; U.S. Code 1970). Among these are National Ambient Air Quality Standards (NAAQS) which were established by U.S. Environmental Protection Agency (EPA) for six criteria air pollutants to protect public health and the environment. The implication of the NAAQS is that states with areas in exceedance bear the burden of becoming compliant. Namely, when NAAQS are exceeded, states must develop permanent and enforceable air pollution control measures and demonstrate that the area will meet the standard as a result of the measures which imposes costs on public and private sectors. Since 1990, average concentrations of fine particulate matter ($PM_{2.5}$) have decreased by over 37% (EPA 2015). Nationwide reductions in $PM_{2.5}$ are responsible for the largest benefits tied to the CAA due to documented improvements to health (EPA 2009; OMB 2015). However, studies have not yet demonstrated if expected public health benefits from improving air quality are comparable in nonattainment counties for $PM_{2.5}$ NAAQS and counties in compliance.

Numerous epidemiologic studies have demonstrated that mortality and other health endpoints are associated with both short-term (Laden et al. 2000; Schwartz et al. 1996) and long-term (Dockery et al. 1993; Krewski et al. 2005) exposures to $PM_{2.5}$. Studies have also demonstrated that reductions in long-term exposures to $PM_{2.5}$ are associated with reductions in mortality rates and increased life expectancy (Correia et al. 2013; Pope et al. 2009; Schwartz et al. 2015; Wang et al. 2016; Zeger et al. 2008). Moreover, studies have also documented immediate improvements in health outcomes when significant sources of air pollution were abruptly shut down or controlled (Breitner et al. 2009; Clancy et al. 2002; Peel et al. 2008; Pope et al. 1992; Su et al. 2015; Wang et al. 2009). Combined with toxicology studies, this body of research formed the scientific basis for a weight-of-evidence determination of a causal relationship between fine particulate matter ($PM_{2.5}$) and cardiovascular mortality (EPA 2009).

Few studies have focused on specifically NAAQS-induced reductions in particle pollution and consequent benefits on public health. Previously, Chay et al. (2003) concluded that counties in nonattainment of the standard for total solid particulates (TSP), showed a larger reduction in TSP in the year following the CAA, but this improvement in air quality had little association with declines in either adult or elderly mortality. Zigler et al. (2012) estimated that the 1991 nonattainment designations for PM_{10} causally reduced mortality but found that the effect estimates were similar in areas where regulations decreased and where they did not decrease PM_{10} concentrations. Studies on the effectiveness of regulation, "accountability studies," have not yet focused on improvements in health due to annual $PM_{2.5}$ NAAQS regulatory actions.

With this study, we focused on the impact of the 1997 NAAQS designations on the association between the changes in cardiovascular mortality rates and in annual $PM_{2.5}$. The first standard for annual $PM_{2.5}$ was set in 1997, but the attainment designations were not promulgated until 2005. We compared age-adjusted standardized cardiovascular mortality rates in 619 counties before and after the NAAQS were promulgated (2000-2004 vs 2005-2010). Additionally, we examined how the association varied between counties stratified by attainment designation and by design values used in the designation process to characterize air quality. The primary research question of this study ultimately contributes to the discussion on the significance of NAAQS and other EPA regulatory actions as they relate to changes air pollution and associated health concerns.

CHAPTER 2: METHODS

Data

Mortality Rates

Annual mean cardiovascular standardized age-adjusted mortality rates (annual deaths per year per 100,000 people) were calculated for years between 2000 and 2010. With individual level data from U.S. National Center for Health Statistics (NCHS) we calculated crude cardiovascular mortality rates by dividing the number of cardiovascular deaths [*International Classification of Diseases, 10th Revision* (ICD 10) codes 0.0-79.9] in an age group, county, and year by the total population of that age group in the corresponding county and year. The crude mortality rates were then age-adjusted by averaging across all age groups and weighting to the national population age distribution. The standard errors for the mortality rates were calculated using NCHS standard formulas which assume population is known and the number of deaths has a Poisson distribution. Uncertainty in the mortality rates arises from short-term fluctuation in the number of deaths from random factors (e.g. extreme weather or changes to available medical care) and short-term fluctuation in population estimates (e.g. transient or seasonal moves) for years between decennial census counts, regardless of a constant long-term mortality rate and population. Annual data was averaged before and after promulgation of the NAAQS: period 1 (2000-2004) (pd1) and period 2 (2005-2010) (pd2).

Similarly, we calculated standardized age-adjusted mortality rates for chronic obstructive pulmonary disease (COPD) to approximate accumulated exposure to smoking (Pope et al. 2009).

$PM_{2.5}$ annual data

Annual average $PM_{2.5}$ data was calculated for years 2000 to 2010 using data from EPA's Air Quality System (AQS) which documents air quality measured at environmental monitors across the U.S. whose locations are based on population density. For counties with multiple $PM_{2.5}$ monitors, the annual means of all monitors within the county were averaged. Monitors were included if they reported for at least 45 days of the year to coincide with monitoring regulations which require 75% of days per reporting quarter collected assuming a minimum recording frequency of one in six days (365/6*0.75).

Annual $PM_{2.5}$ data were also averaged to period 1 (2000-2004) (pd1) and period 2 (2005-2010) (pd2), before and after attainment designations. The complete annual $PM_{2.5}$ monitoring data included 775 counties. However, 69 counties did not have $PM_{2.5}$ records for any years 2000-2004, and 87 counties did not have records in 2005-2010. The loss of data may be attributed to several different factors, including location change of monitor within a metropolitan statistical area (MSA), monitor shut down, or population changes in an MSA. Thus, analysis considered 619 counties with monitored annual mean $PM_{2.5}$ in both period 1 and period 2.

Sociodemographic characteristics

County-level socioeconomic status (SES) and demographic variables were obtained from the U.S. Bureau of the Census for 2000 and 2010. Variables included total income (in tens of thousands of U.S. dollars), percent with at least a high school degree (of population 25 years and older), percent Hispanic (of total population), and percent black (of total population). For the purpose of this study, changes in socio-demographic variables refer to the differences between Census 2000 and Census 2010 statistics (2010 minus 2000).

Mortality rates, air monitoring data, and Census data were matched by five-digit county FIPS (federal information processing standard) codes, providing complete data for 619 counties.

Modification of the effect by NAAQS

The EPA designates NAAQS attainment status based on a number of factors including ambient monitor values, meteorology, weather, geography, contributions to neighboring areas, etc. The first factor considered in designation is the highest recorded design value (DV) of any monitor in the county. For annual $PM_{2.5}$, the DV is defined as the three year rolling average concentration, calculated at each monitor based on annual weighted means based on quarterly means (40 C.F.R. §1.50 App. N 2013). Counties without monitors or counties with DVs below the NAAQS may still be declared in nonattainment due to the other factors in the designation analysis as mentioned above. Design values may be accessed in the AQS while attainment/nonattainment status is identified in the EPA Green Book, which houses designations for all criteria pollutants (EPA 2016).

Out of 208 total counties designated in nonattainment for the 1997 annual $PM_{2.5}$ standard, our primary analysis included 133 nonattainment counties. Counties without $PM_{2.5}$ data for period 1 and/or period 2 were dropped. The first designations, published in 2005, were made using the 2003 DV. For our secondary analysis, we selected the highest DV in the county for each year. If a county did not have at least five design values recorded from 2000 to 2010, with at least one value each in period 1 and period 2, it was removed from this analysis due to lack of sufficient records. Counties without 2003 design values were also excluded.

Statistical Analysis

Linear regression models were used to capture the association between the change in cardiovascular mortality rate, period 1 (2000-2004) minus period 2 (2005-2010), and the change in $PM_{2.5}$ levels, period 1 minus period 2, in U.S. counties. The association was evaluated by three different covariate models—models 1, 2, and 3 (Table 2). Model 1 adjusted for initial cardiovascular mortality rate. Model 2 adjusted for strong confounders of the $PM_{2.5}$-mortality relationship—initial cardiovascular mortality rate, change in COPD rate, and change in total income. Model 3 was adjusted by (a) initial period 1 cardiovascular mortality rate, (b) change in COPD, (c) change in total income, (d) change in percent with high school degree, (e) change in percent Hispanic, and (f) change in percent black. Bayesian Information Criteria (BIC) was used to determine which covariate model best fit the data. A model with a lower value of BIC is preferred.

All models in the statistical analysis were weighted by the inverse variances (ω^2) of the estimated rate. The weights were also proportional to the total population (correlation = 0.96), giving more weight to counties with greater populations. The general multiple regression equation can be summarized by:

$$\Delta y_i = \beta_0 + \beta_1 \Delta PM_i + \beta_2 x_{2i} + \ldots + \beta_p x_{pi} + \varepsilon_i, \quad \varepsilon_i \sim N(0, \sigma^2/\omega^2)$$

The model expresses the relationship between the dependent variable (ΔY)—reduction in cardiovascular mortality rate—and p independent variables (Xs)—change in $PM_{2.5}$ (ΔPM) and change in aforementioned covariates. Regression coefficients (β_j) express the estimated expected change in Δy and per unit increase in x_j (j from 1 to p). The independent variables were centered on their weighted means so that the model intercept (β_0) is interpreted as the weighted mean change in mortality rate. Our results focus on the resultant β_1 which captures the expected change in annual mortality rates (Δy_i) for each unit decrease in $PM_{2.5}$.

A directed acyclic graph was used to visually represent the association between change in $PM_{2.5}$ and change in cardiovascular mortality rate with consideration of confounders to the association based off prior knowledge (Figure 1). By adding to the linear regression model certain variables – those boxed in the diagram – we controlled for the effects of confounding from all identified variables as no pathway between exposure and outcome was left unblocked.

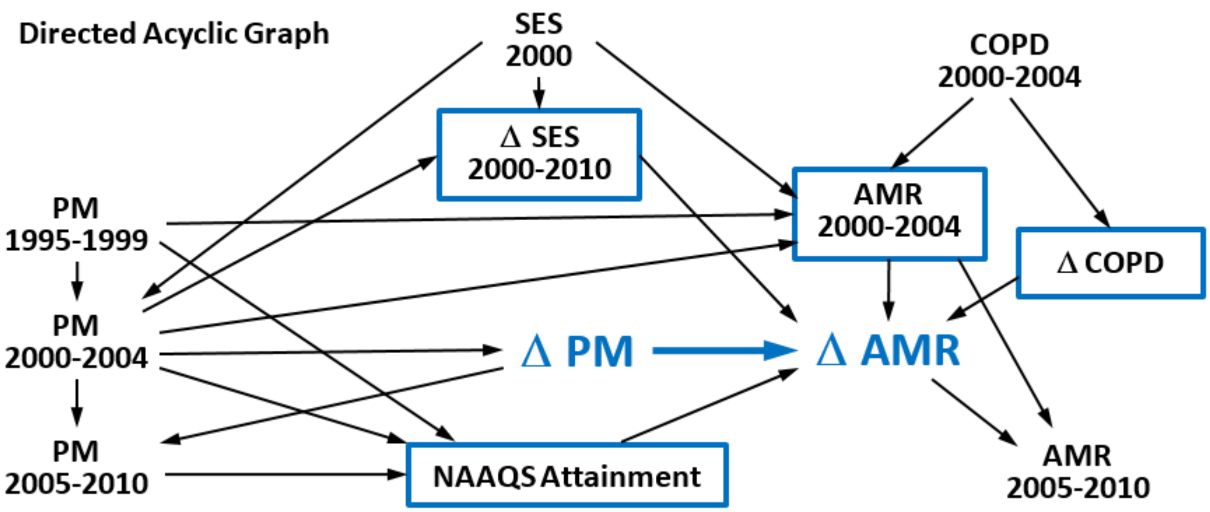

Figure 1. Directed Acyclic Graph indicating association between change in PM2.5 (ΔPM) and change in age-adjusted cardiovascular mortality rate (ΔAMR) from period 1 (2000-2004) to period 2 (2005-2010) as adjusted for confounding variables. Abbreviations—PM: average $PM_{2.5}$; AMR: average age-adjusted cardiovascular mortality rate; SES: socioeconomic status variables, including race, ethnicity, income, education status; COPD: chronic obstructive pulmonary disease, a proxy for smoking status; NAAQS Attainment: 1997 annual $PM_{2.5}$ National Ambient Air Quality Standard designation status

Next, we compared the change in age-adjusted cardiovascular mortality rates for nonattainment versus attainment counties. We additionally examined the change in cardiovascular mortality rate in counties stratified on the 2003 design value (DV). We stratified around thresholds of 12 $\mu g/m^3$ (the current annual $PM_{2.5}$ standard) and 15 $\mu g/m^3$, to consider the influence of the initial level of $PM_{2.5}$ in a county at the time of the first NAAQS designation. The changes to health were characterized as a total difference between the two periods, adjusted for covariates, as well as an incremental change per unit drop in $PM_{2.5}$, adjusted for covariates.

TABLE 1. Summary statistics, means (with parenthetical interquartile ranges), for exposure, outcome, and covariates for all counties and counties in strata used to assess effect modification. Deltas for $PM_{2.5}$, cardiovascular mortality, and COPD mortality were calculated period 1 (2000-2004) minus period 2 (2005-2010) so positive values represent improvement in air quality or health. Deltas for covariates were calculated 2010 minus 2000 so positive values represent increase in value for the given variable.

	All Counties	Attainment	Nonattainment	DV03 ≤ 12	12< DV03 ≤15	15 < DV03
Counties Included, n	619	486	133	165	221	81
Cardiovascular Mortality Rate, pd 1	323 (72.1)	320 (78.7)	335 (43.6)	299 (59.4)	339 (71.3)	345 (50.4)
Cardiovascular Mortality Rate, pd 2	262 (67.7)	261 (69.3)	268 (54.3)	242 (53.2)	274 (59)	280 (50.2)
Δ Cardiovascular Mortality Rate (pd1-pd2)	61.2 (22.1)	59.5 (25.4)	67.1 (16.3)	56.6 (25.8)	65.1 (20.9)	64.8 (16)
(deaths per 100,000 people)						
$PM_{2.5}$ concentration, pd 1	12 (3.92)	11.1 (3.39)	15.3 (2.06)	9.66 (2.6)	13.5 (1.48)	16.2 (1.15)
$PM_{2.5}$ concentration, pd 2	10.8 (3.35)	10.2 (3.28)	13.2 (1.97)	8.89 (2.82)	12 (1.38)	13.9 (1.09)
Δ $PM_{2.5}$ concentration (pd1-pd2)	1.21 (1.3)	0.969 (1.33)	2.1 (0.779)	0.778 (1.02)	1.5 (0.878)	2.29 (1.2)
($\mu g/m^3$)						
COPD Mortality Rate, pd 1	47.5 (15.6)	48.3 (14.9)	44.7 (17.2)	47.3 (15.6)	46.3 (15)	47.4 (17.1)
COPD Mortality Rate, pd 2	47.4 (17.1)	48.5 (16.5)	43.6 (19)	46.5 (17.6)	46.7 (15.9)	47 (18.9)
Δ COPD Mortality Rate (pd1-pd2)	0.125 (7.89)	-0.144 (8.69)	1.11 (5.63)	0.83 (8.23)	-0.417 (7.9)	0.479 (4.92)
(deaths per 100,000 people)						
Total Income 2000	8.02 (7.66)	5.96 (5.35)	15.5 (14.8)	7.9 (8.08)	8.11 (6.74)	16.3 (12.7)
Total Income 2010	8.41 (8.54)	6.39 (5.84)	15.8 (15.5)	8.62 (9.11)	8.44 (6.99)	16.4 (14.5)
Δ Total Income (2010-2000)	0.395 (0.533)	0.431 (0.478)	0.266 (0.944)	0.724 (0.816)	0.334 (0.516)	0.0573 (0.822)
(tens of thousands of U.S. dollars)						
Percent High School Educated 2000	80.7 (8.35)	80.6 (8.4)	80.7 (8)	82.3 (8.1)	79.9 (8.8)	78.7 (7.4)
Percent High School Educated 2010	85.5 (6.6)	85.5 (6.83)	85.5 (6.2)	86.6 (6.3)	84.7 (6.9)	83.9 (6.3)
Δ Percent High School Educated (2010-2000)	4.82 (2.7)	4.8 (2.7)	4.86 (2.3)	4.3 (2.8)	4.84 (2.6)	5.22 (1.8)
(percent of population age >25 high school degree)						
Percent Black Population 2000	11.7 (15)	11.2 (15.1)	13.6 (14.9)	7.24 (9.14)	15.7 (19.8)	16.3 (16.7)
Percent Black Population 2010	12.7 (15.7)	12.1 (15.4)	15.1 (15.9)	8.07 (10.4)	17 (20.3)	17.6 (19.5)
Δ Percent Black Population (2010-2000)	1.03 (1.4)	0.913 (1.35)	1.46 (1.5)	0.833 (1.18)	1.28 (1.73)	1.32 (1.53)
(percent of total population)						
Percent Hispanic Population 2000	7.82 (6.54)	7.53 (5.53)	8.89 (9.27)	11.3 (10.2)	5.42 (5.09)	9.81 (6.76)
Percent Hispanic Population 2010	10.6 (10)	10.2 (8.53)	12 (13.3)	14.5 (14.4)	8.04 (7.27)	12.7 (10)
Δ Percent Hispanic Population (2010-2000)	2.79 (2.84)	2.71 (2.66)	3.1 (3.64)	3.19 (3.06)	2.62 (2.6)	2.92 (3.06)
(percent of total population)						

CHAPTER 3: RESULTS

Population Characteristics

The association between change in cardiovascular mortality rate and the change in $PM_{2.5}$ as well as modification of that association by attainment status was analyzed for 619 counties, capturing 70% of the U.S. population (2010). Modification of the association by design value was analyzed in 467 counties, capturing 61% of the U.S. population.

From period 1 (2000-2004) to period 2 (2005-2010), overall cardiovascular mortality rate, decreased on average by 61.2 deaths per year per 100,000 people annually with an interquartile range (IQR) of 22.1 deaths per year per 100,000 people (Table 1). Annual $PM_{2.5}$ decreased on average by 1.21 $\mu g/m^3$ with an IQR of 1.3 $\mu g/m^3$. COPD mortality rates also decreased on average from period 1 to period 2 by 0.125 deaths per year per 100,000 people. From 2000 to 2010, total household income increased by $3,950 and there was a 4.82% increase in the population with at least a high school degree of age 25 or older. Hispanic and black populations also increased over the study period by 2.79% and 1.03%, respectively.

The strongest predictor of change in cardiovascular mortality rate was a county's cardiovascular mortality rate during period 1 (Figure A.3); therefore, we included initial-period cardiovascular mortality rate as an explanatory variable. Period 1 cardiovascular mortality rates were also correlated to the average $PM_{2.5}$ concentrations in period 1 (Figure A.4). Finally, there was a strong correlation between the change in $PM_{2.5}$ concentrations from period 1 to period 2 and the period 1 concentration of $PM_{2.5}$ ($\rho = 0.57$, 0.76 when weighted), indicating areas with the highest initial levels of $PM_{2.5}$ had the largest declines in $PM_{2.5}$ (Figure A.5).

Main Result

The estimated impact of reductions in $PM_{2.5}$ on reductions in cardiovascular mortality was consistent across the three models, ranging from 0.99 (95% CI 0.27, 1.71) deaths per year per 100,000 people to 1.44 (95% CI 0.73, 2.14) fewer deaths per year per 100,00 people per unit (1 $\mu g/m^3$) decrease in $PM_{2.5}$ (Table 2). Added variables altered the estimate of the mean effect and improved the model fit (BIC analysis), suggesting confounding effects of additional predictors on the association between of the decrease in $PM_{2.5}$ and decrease in cardiovascular mortality rate. Model 3 fit the data best (BIC), estimating a drop in mortality rate of 1.10 (95% CI 0.37, 1.82) fewer deaths per year per 100,000 people was associated with 1 $\mu g/m^3$ reduction in $PM_{2.5}$ across U.S. counties.

Model 3 also estimated 0.168 fewer deaths per year per 100,000 people were associated with each unit increase (1 death per year per 100,000 people) in initial (period 1) cardiovascular mortality rate (Table 2). Each unit decrease in the COPD morality rate (1 fewer COPD death per year per 100,000 people) was associated with 0.256 fewer cardiovascular deaths per year per 100,000 people. Model 3 coefficients also estimate 0.304 fewer cardiovascular deaths per year per 100,000 people were associated with each ten thousand dollar-increase in total household income and 0.431 fewer deaths per year per 100,000 people were associated with each 1% increase in Hispanic population (percent of total population). Finally, 1.52 more cardiovascular deaths per year per 100,000 people were associated with each 1% increase in percent of population aged 25+ that had at least a high school degree and 0.314 more deaths per year per 100,000 people were associated with each 1% increase in Black population (percent of total population). Henceforth, we present results using models adjusting for all covariates of Model 3.

TABLE 2. Results of Selected Regression Models for County-Level Analysis; The reported values are the estimated changes in age-adjusted cardiovascular mortality rate associated with each variable listed on the left. Positive coefficients indicate improvement in mortality rate, fewer deaths per year per 100,000 people. Standard error of average effect estimate is given in parentheses. n = 619.

Variable	Model 1	Model 2	Model 3
(Intercept)	63.1 (0.48)	63.1 (0.47)	63.1 (0.46)
Reduction in $PM_{2.5}$ ($\mu g/m^3$)	1.44 (0.36)	0.99 (0.37)	1.1 (0.37)
Cardiovascular Mortality Rate, pd 1	0.124 (0.01)	0.144 (0.01)	0.168 (0.01)
Δ COPD Mortality Rate	--	0.364 (0.13)	0.256 (0.13)
Δ Income Total (in $10,000 USD)	--	0.534 (0.16)	0.304 (0.17)
Δ Percent High School Educated (%)	--	--	-1.52 (0.31)
Δ Percent Hispanic Population (%)	--	--	0.431 (0.21)
Δ Percent Black Population (%)	--	--	-0.314 (0.27)

First, we examined effect modification by counties designated nonattainment versus attainment of the 1997 standard. Second, we examined effect modification by counties stratified based off the first factor in the designation analysis—the 2003 design value, an indicator for initial PM and the first of five criteria used to determine attainment status for the 1997 standard.

Association Modified by Attainment Status

The average decrease in $PM_{2.5}$ in nonattainment counties from period 1 to period 2, 2.10 $\mu g/m^3$, was roughly twice that in attainment counties 0.97 $\mu g/m^3$ (Table 1; Figure A.1). Nonattainment counties also had a greater decrease in mortality rate (63.7 (95% CI 62.2, 65.3) deaths per year per 100,000), adjusted for confounders, than attainment counties (62.7 (95% CI 61.5, 64.0) deaths per year per 100,000) when $PM_{2.5}$ was not included as an explanatory variable (Figure 2a). The difference between estimates, however, was not statistically significant. Per unit decrease in $PM_{2.5}$, counties in nonattainment had a smaller change in mortality rate (0.59 (95% CI -0.54, 1.71) deaths per year per 100,000 people) compared to counties in attainment (1.96 (95% CI 0.77, 3.15) deaths per year per 100,000 people), but this difference was not statistically significant (Figure 2b).

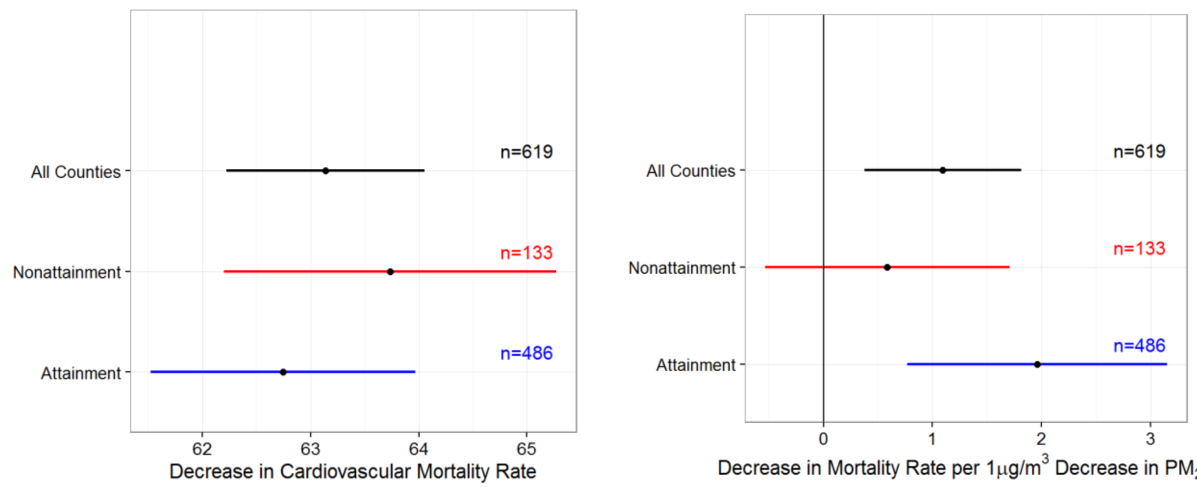

Figure 2. (a) Point estimate and 95% confidence intervals for a decrease in cardiovascular mortality rate for all counties, nonattainment counties, and attainment counties—adjusted for confounders included in Model 3 but not $PM_{2.5}$ (b) Point estimate and 95% confidence intervals for effect of a per unit decrease in $PM_{2.5}$ on decrease in cardiovascular mortality rate for all counties, nonattainment counties, and attainment counties—adjusted for confounders included in Model 3.

Association Modified by Design Value

Counties with a 2003 DV greater than 15 μg/m^3 experienced the greatest decrease in mean annual $PM_{2.5}$ (2.29 μg/m^3) from period 1 to period 2 (Table 1; Figure A.2). County-level observed changes in PM in each group are given by Figure A.2. Similarly, the mean decline in cardiovascular mortality rate for these same counties (64.5 (95% CI 62.5, 66.6) deaths per year per 100,000), adjusted for confounders but not changes in $PM_{2.5}$, exceeds the mean decline in mortality rate in counties with the lowest 2003 DVs (62.3 (95% CI 60.4, 64.2) deaths per year per 100,00), though the difference is not statistically significant (Figure 3a). Per unit $PM_{2.5}$, however, counties with the highest 2003 DVs had an incremental decline in cardiovascular mortality rate (0.73 (95% CI -0.57, 2.02) fewer deaths per year per 100,000 per 1 μg/m^3 drop) that was three times less than that of counties with 2003 DV below 12 μg/m^3 (2.6 (95% CI 0.52, 4.70) fewer deaths per year per 100,000 per 1 μg/m^3 drop), though the difference was not statistically significant (Figure 3b). For all estimates of $PM_{2.5}$ and mortality change from period 1 to period 2, the estimates for counties with 2003 DV greater than 12 μg/m^3 and less than or equal to 15 μg/m^3 fell between those of the other two groups and were not statistically different.

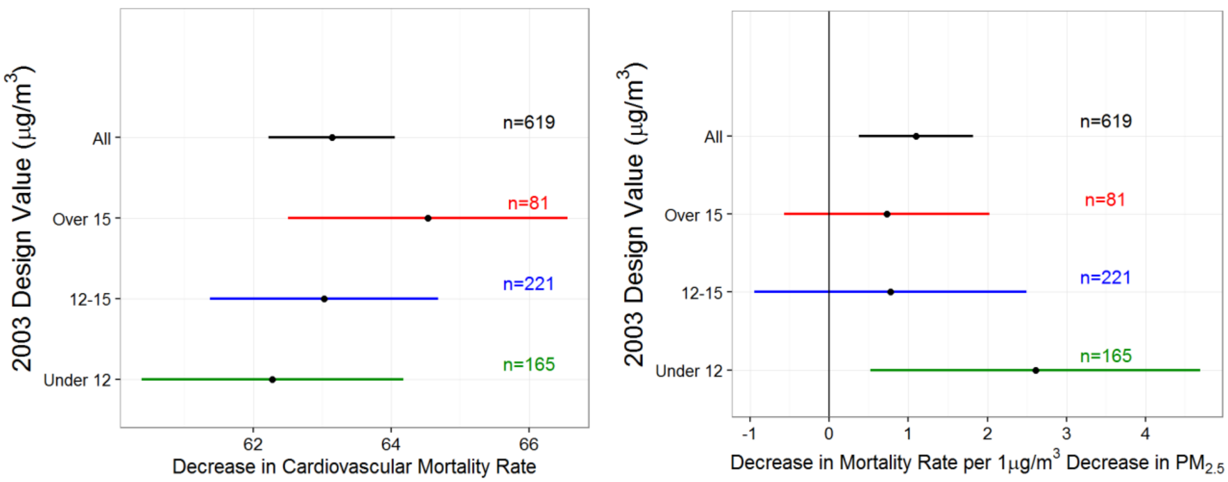

Figure 3. (a) Point estimate and 95% confidence intervals for decrease in cardiovascular mortality rate for all counties and counties with 2003 Design Value (DV03) greater than 15 μg/m^3, between 12 and 15 μg/m^3, and under 12 μg/m^3—adjusted for confounders included in Model 3 but not $PM_{2.5}$. (b) Point estimate and 95% confidence intervals for effect of a per unit decrease in $PM_{2.5}$ on decrease in cardiovascular mortality rate for all counties and counties with 2003 DV greater than 15 μg/m^3, between 12 and 15 μg/m^3, and under 12 μg/m^3—adjusted for confounders included in Model 3.

CHAPTER 4: CONCLUSIONS

We estimate the association between the change in cardiovascular mortality rate and the change in annual $PM_{2.5}$ across 619 US counties and examine how the association varied by counties' attainment status for 1997 annual $PM_{2.5}$ NAAQs. A decrease in 1 $\mu g/m^3$ of $PM_{2.5}$ was associated with 1.10 (95% CI 0.37, 1.82) fewer deaths per year per 100,000 people. When we examined the same association by attainment status and by initial DV, we found that nonattainment counties as well as those with the greatest initial levels of $PM_{2.5}$, experienced greater average declines in $PM_{2.5}$ (2.1 $\mu g/m^3$ and 0.97 $\mu g/m^3$, respectively) but smaller improvements to health per unit drop in $PM_{2.5}$ (respectively, 0.59 (95% CI -0.54, 1.71) and 0.73 (95% CI -0.57, 2.02) fewer deaths per year per 100,000 people), although these were not statistically different. Meanwhile, attainment counties with cleaner air experienced smaller declines in $PM_{2.5}$ (0.97 $\mu g/m^3$) but greater improvement to health per unit drop in $PM_{2.5}$ (1.96 (95% CI 0.77, 3.15) fewer deaths per year per 100,000). However, the differences in health improvement were not statistically significant. The initial $PM_{2.5}$ was higher among nonattainment counties and the change in $PM_{2.5}$ was highly correlated with initial $PM_{2.5}$ (Figure A.1).

The average drop in cardiovascular mortality attributed to the reductions in $PM_{2.5}$ (the product of the average incremental effect from Figure 2b and the average drop in $PM_{2.5}$ from Table 1) was approximately 1.24 deaths per year per 100,000 people in nonattainment counties and 1.9 deaths per year per 100,000 in attainment counties. Though multiple risk factors interact to contribute to health improvement, these results suggest that 1.9% and 3.0% of the overall decrease in cardiovascular mortality rate is attributed to the decline in $PM_{2.5}$ in nonattainment and attainment counties, respectively. In counties with 2003 DV greater than 15 $\mu g/m^3$, 1.67 fewer deaths per year per 100,000 people were attributed to reductions in $PM_{2.5}$ (3.2% of total health improvement) while, in counties with 2003 DV less than 12 $\mu g/m^3$, 2.03 fewer deaths per year per 100,000 people were attributed to $PM_{2.5}$ reductions (2.6%).

Our results also suggest that health benefit per unit drop in $PM_{2.5}$ persists in the counties with $PM_{2.5}$ levels at and below 12 $\mu g/m^3$, our current national standard for annual $PM_{2.5}$. At lower levels of $PM_{2.5}$, a unit decrement in $PM_{2.5}$ is associated with greater expected health improvement in a county. Taken together, these findings suggest that the concentration response function between $PM_{2.5}$ and cardiovascular mortality rate is nonlinear with a concave down shape, having a steeper slope at lower values of $PM_{2.5}$ and a less steep slope higher concentrations.

CHAPTER 5: DISCUSSION

The main result is supported by studies which find a significant association between health improvements and the decline in annual $PM_{2.5}$. Pope et al. (2009) estimated an increase in mean life expectancy of 0.61±0.2 years was associated with a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ in the 1980s and 1990s, and Correia et al. (2013) reported a 10 $\mu g/m^3$ decrease was associated with an increase in mean life expectancy of 0.35 years from 2000 to 2007. "Quasi-experimental" studies, have reported significant absolute improvements to health when abrupt, dramatic improvements to air quality have occurred as a result of a local event or source-control action (Breitner et al. 2009; Clancy et al. 2002; Peel et al. 2008; Pope et al. 1992; Su et al. 2015; Wang et al. 2009). Pope et al. (1992) first demonstrated a significant reduction in daily mortality after PM_{10} concentrations dropped dramatically due to the temporary closure of a steel mill in the Utah Valley. After a 1990 ban on bituminous coal in Dublin, Ireland, Clancy et al. (2002) reported a sharp reduction in black smoke and sulfur dioxide along with a 10.3% reduction in cardiovascular deaths or about 243 fewer cardiovascular deaths per year. Examining a more recent sudden change in air pollution, Su et al. (2015) reported unique air pollution controls for the Beijing 2008 Summer Olympics successfully led to reduction of air pollution—measured by PM_{10}, $PM_{2.5}$, particle number concentration (PNC), and NO_2—and a decreased risk of cardiovascular mortality. When the unique controls ended post-Olympics, air pollution increased and was associated with increases in cardiovascular mortality. Our report of overall improvement in health after the implementation of NAAQS, though over a relatively longer time period, is in accordance with these studies.

On the other hand, previous studies which examined impacts of broader, as opposed to localized and immediate, air pollution requirements were unable to conclude that national regulations were associated with changes in both air quality and health. In evaluating the changes in total suspended particles (TSPs) induced by the Clean Air Act Amendments in 1970, Chay et al. (2003) found that TSP concentrations declined significantly more in nonattainment counties compared to attainment counties. However, he reported that nonattainment status had little association with changes in adult or elderly mortality rates. Further, the authors demonstrated that attainment and nonattainment counties very near to the 1970 TSP standard at the time of legislation had similar characteristics—an element that may have reduced omitted variable bias. This strength, unfortunately, may have been undermined by the difference in initial health status between attainment and nonattainment counties (Chay et al. 2003). Considering attainment status for the annual PM_{10} NAAQS, Zigler (2016) reported that the 1991 designations overall caused 1.76 fewer deaths per 1,000 Medicare beneficiaries. However, using principal stratification, the authors indicated that the magnitude of negative dissociative effects was similar to the negative associative effects, meaning that the regulation causally reduced morality regardless of whether the regulation causally reduced average concentrations of PM_{10}.

Our study considers 1997 NAAQS designations for $PM_{2.5}$ and reports a strong improvement to health per unit drop in $PM_{2.5}$ for counties in attainment. Relative to nonattainment counties, attainment counties are lower on the concentration response curve and have a steeper slope. This is also consistent with literature which supports the persistence of the association at levels of $PM_{2.5}$ at or below the current NAAQS of 12 $\mu g/m^3$, indicating that health will continue to improve as areas ambient concentrations of $PM_{2.5}$ decline (Crouse et al. 2012;

Daniels 2004; Marshall et al. 2015; CA Pope et al. 2015; Schwartz et al. 2002; Schwartz et al. 2008).

Moreover, the analyses of Marshall et al. (2015), CA Pope et al. (2015), and others also propose a supralinear (concave downward) $PM_{2.5}$-mortality concentration response (C-R) function, in agreement with conclusions presented here (Crouse et al. 2012; Lu et al. 2017; Marshall et al. 2015; CA Pope, 3rd et al. 2015). CA Pope et al. (2015) reported that there are health benefits from reducing air pollution in more polluted areas and even greater health benefits per unit drop in $PM_{2.5}$ from continuing to reduce air pollution in cleaner areas. Putting emphasis on U.S. conditions, Marshall et al. (2015) concluded that a supralinear C-R for cardiopulmonary mortality and $PM_{2.5}$ implies we should achieve greater health benefit and economic efficiency by making "blue skies bluer", although this optimal policy might conflict with traditional environmental equity goals.

Our study faces a number of challenges common to long-term accountability studies. First, nonattainment counties are clustered in or nearby urban areas and have different socio-economic, demographic (SES) characteristics compared to attainment counties. Despite controlling for changes in SES variables in our statistical model, it is possible that we did not totally remove confounding.

Second, annual $PM_{2.5}$ NAAQS are not solely responsible for nationwide reductions to annual $PM_{2.5}$. Technological advancements and decreasing costs of clean technology as well as other air quality regulations and programs have reduced $PM_{2.5}$ and its precursors. National fuel standards target mobile emission sources across all counties while NAAQS for NO_x, SO_x, and ozone have their own attainment designations and associated control requirements which do not necessarily align with designations for $PM_{2.5}$ NAAQS used here. Because such programs differentially impact all counties—not simply the attainment versus nonattainment groups used for this study—it is difficult to identify the change to $PM_{2.5}$ and subsequent change to health attributed to a particular program in a particular county. Finally, the annual $PM_{2.5}$ NAAQS as well as most other regulations target a single air pollutant, but they may influence concentrations of multiple pollutants which interact to affect health through more complex and unaccounted for pathways.

This study has affirmed that reductions in $PM_{2.5}$ are significantly associated with reductions in age-adjusted cardiovascular mortality rates. Further, we report that the health benefits per unit drop in $PM_{2.5}$ varied but were not statistically different between the counties grouped by designation status or initial level of $PM_{2.5}$. We hypothesize that the $PM_{2.5}$-mortality concentration response function is nonlinear with cleaner counties experiencing greater improvement per unit $PM_{2.5}$.

APPENDIX A

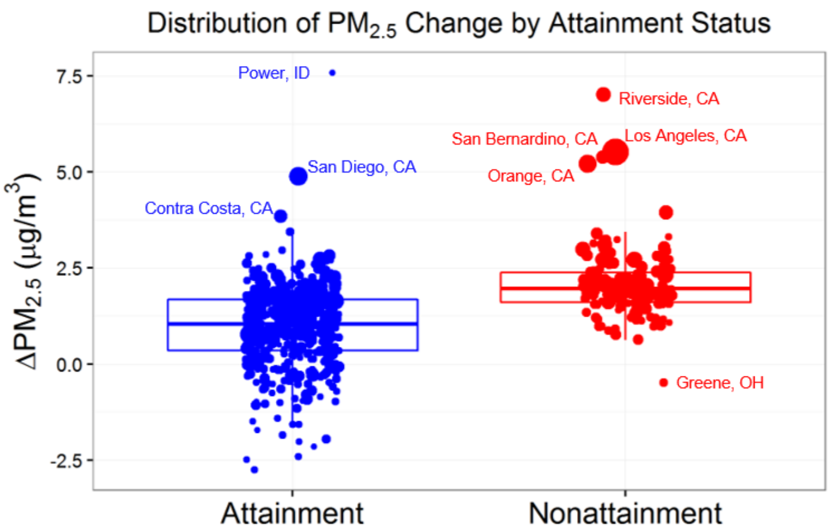

Figure A.1. Reduction in $PM_{2.5}$ (period 1 minus period 2) in attainment versus nonattainment counties. Each point represents the observed average drop in $PM_{2.5}$ in a county with size given by the inverse variance for change in cardiovascular mortality rate, also proportional to population size of county.

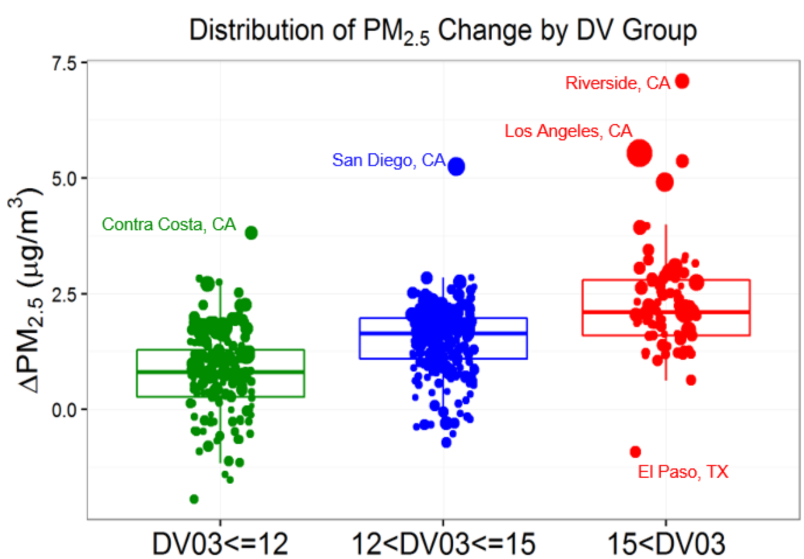

Figure A.2. Reduction in $PM_{2.5}$ (period 1 minus period 2) in counties with 2003 design value (DV) less than or equal to 12 $\mu g/m^3$, 2003 DV between 12 $\mu g/m^3$ and 15 $\mu g/m^3$, and DV 2003 greater than 15 $\mu g/m^3$. Each point represents the observed average change in $PM_{2.5}$ in a county with size given by the inverse variance for change in cardiovascular mortality rate, also proportional to population size of county.

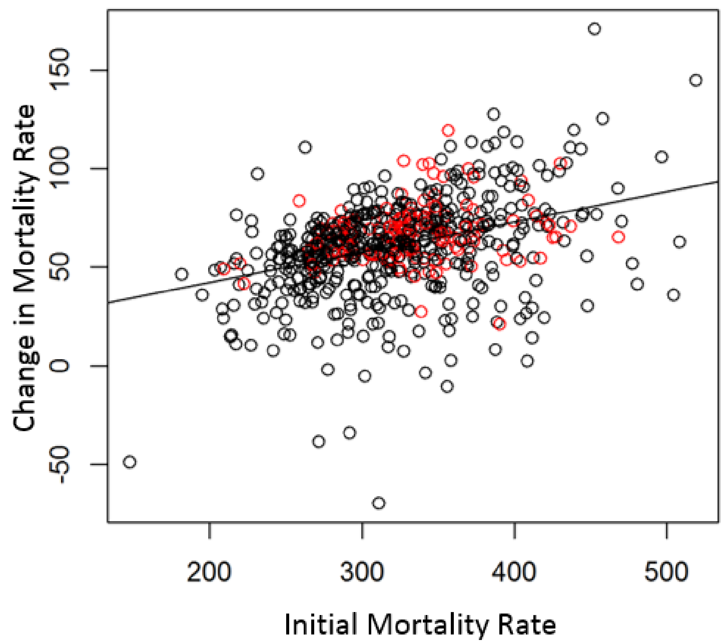

Figure A.3. Linear fit to the association between average initial cardiovascular mortality rate, period 1 (2000-2004), and the decrease in cardiovascular morality rate from period 1 (2000-2004) to period 2 (2005-2010) with nonattainment counties given in red.

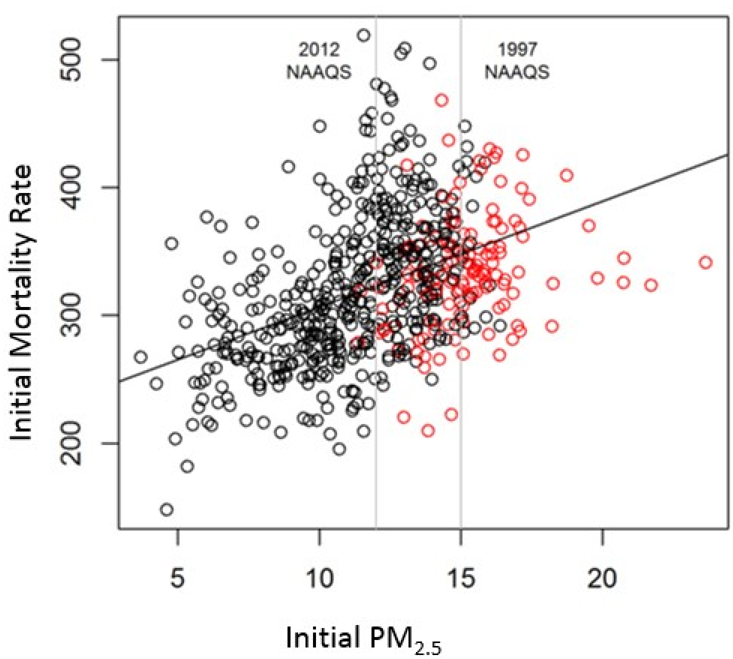

Figure A.4. Linear fit to the association between initial $PM_{2.5}$, the average in period 1 (2000-2004), and the decrease in $PM_{2.5}$ from period 1 (2000-2004) to period 2 (2005-2010) with nonattainment counties given in red.

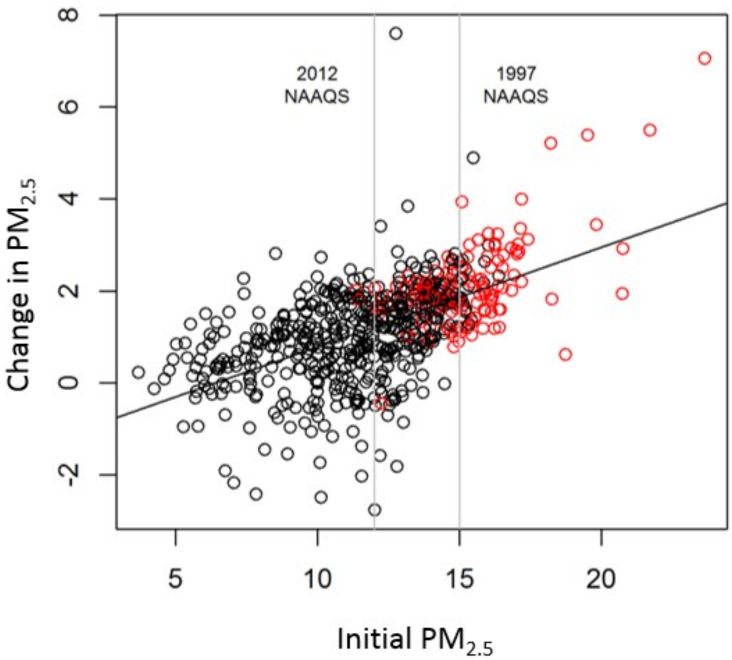

Figure A.5. Linear fit to the association between initial $PM_{2.5}$, the average in period 1 (2000-2004), and the decrease in $PM_{2.5}$ from period 1 (2000-2004) to period 2 (2005-2010) with nonattainment counties given in red.

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