Effect of Air Pollution Control on Life Expectancy in the United States

An Analysis of 545 U.S. Counties for the Period from 2000 to 2007

Andrew W. Correia,[a] *C. Arden Pope III,*[b] *Douglas W. Dockery,*[c] *Yun Wang,*[a] *Majid Ezzati,*[d] *and Francesca Dominici*[a]

Background: In recent years (2000–2007), ambient levels of fine particulate matter ($PM_{2.5}$) have continued to decline as a result of interventions, but the decline has been at a slower rate than previous years (1980–2000). Whether these more recent and slower declines of $PM_{2.5}$ levels continue to improve life expectancy and whether they benefit all populations equally is unknown.

Methods: We assembled a data set for 545 U.S. counties consisting of yearly county-specific average $PM_{2.5}$, yearly county-specific life expectancy, and several potentially confounding variables measuring socioeconomic status, smoking prevalence, and demographic characteristics for the years 2000 and 2007. We used regression models to estimate the association between reductions in $PM_{2.5}$ and changes in life expectancy for the period from 2000 to 2007.

Results: A decrease of 10 $\mu g/m^3$ in the concentration of $PM_{2.5}$ was associated with an increase in mean life expectancy of 0.35 years (SD = 0.16 years, $P = 0.033$). This association was stronger in more urban and densely populated counties.

Conclusions: Reductions in $PM_{2.5}$ were associated with improvements in life expectancy for the period from 2000 to 2007. Air pollution control in the last decade has continued to have a positive impact on public health.

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From the [a]Department of Biostatistics, Harvard School of Public Health, Boston, MA; [b]Department of Economics, Brigham Young University, Provo, UT; [c]Departments of Environmental Health and Epidemiology, Harvard School of Public Health, Boston, MA; [d]MRC-HPA Centre for Environment and Health and Department of Epidemiology and Biostatistics, Imperial College London, Norfolk Place, St Mary's Campus, London, United Kingdom.

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Editors' note: *A commentary on this article appears on page 32.*

Correspondence: Francesca Dominici, Department of Biostatistics, Harvard School of Public Health, 655 Huntington Avenue, HSPH Building 2, 4th Floor, Boston, MA 02115. E-mail: fdominic@hsph.harvard.edu.

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Since the 1970s, enactment of increasingly stringent air quality controls has led to improvements in ambient air quality in the United States at costs that the U.S. Environmental Protection Agency (EPA) has estimated as high as $25 billion per year.[1] However, even with the well-established link between long-term exposure to air pollution and adverse effects on health,[2] the extent to which more recent regulatory actions have benefited public health remains in question.

Air pollutant concentrations have been generally decreasing in the United States, with substantial differences in reductions across metropolitan areas. Levels of fine particulate matter air pollution (particulate matter <2.5 μm in aerodynamic diameter, $PM_{2.5}$) remain relatively high in some areas. In a 2010 study, the EPA estimated that 62 U.S. counties, accounting for 26% of their total study population, had $PM_{2.5}$ concentrations not in compliance with the National Ambient Air Quality Standards (NAAQS).[3]

Reductions in particulate matter air pollution are associated with reductions in both cardiopulmonary and overall mortality.[2] In the mid-1990s, the Harvard Six Cities Study[4] and the American Cancer Society study[5] reported associations of cardiopulmonary mortality risk with chronic exposure to fine particulate air pollution while controlling for smoking and other individual risk factors. Reanalysis and extended analyses of these studies have confirmed that fine particulate air pollution is an important independent environmental risk factor for cardiopulmonary disease and mortality.[6–12] Additional cohort studies, population-based studies, and short-term time-series studies have also shown associations between reductions in air pollution and reductions in human mortality.[13–21] More recently, studies have suggested an association between $PM_{2.5}$ and life expectancy,[22,23] a well-documented and important measure of overall public health.[24–26]

As our primary analysis, we estimate the association between changes in $PM_{2.5}$ and in life expectancy in 545 U.S. counties during the period from 2000 to 2007. This period is of particular interest, as the EPA restarted wide collection of $PM_{2.5}$ data in 1999–2000, after stopping the nationwide $PM_{2.5}$ monitoring program during the mid-1980s and most of the 1990s. In secondary analyses, we extended to 2007 the data

and statistical analysis originally reported by Pope et al[23] for the period 1980–2000 and investigated whether the relation reported by Pope et al[23] persists in the more recent years.

METHODS

Data

We constructed and analyzed three data sets to estimate the association between changes in life expectancy and changes in $PM_{2.5}$ during the period from 2000 to 2007 in 545 counties (data set 1) and to investigate whether the association previously reported by Pope et al[23] persists when the data on the same 211 counties are extended to the year 2007 (data sets 2 and 3).

Data set 1 included information on 545 U.S. counties for the years 2000 and 2007. These counties include all counties with available matching $PM_{2.5}$ data for 2000 and 2007. Additionally, unlike previous studies in which counties were located only in metropolitan areas,[23] data set 1 comprises counties in both metropolitan and nonmetropolitan areas. Figure 1 shows the counties in this data set shaded according to life expectancy in 2000 and 2007. Variables in this data set were available at the county level, for both 2000 and 2007, and included life expectancy, $PM_{2.5}$, per capita income, population, proportions who were high-school graduates, and proportions who were white, black, or Hispanic. Because data on smoking prevalence were not available for all 545 counties, we used age-standardized death rates for lung cancer and chronic obstructive pulmonary disease (COPD) as proxy variables for smoking prevalence.[27,28] Death rates were calculated in 5-year age groups and age-standardized for the 2000 U.S. population of adults age 45 years or older. Daily $PM_{2.5}$ data were obtained from the EPA's Air Quality System (AQS—http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm). Daily

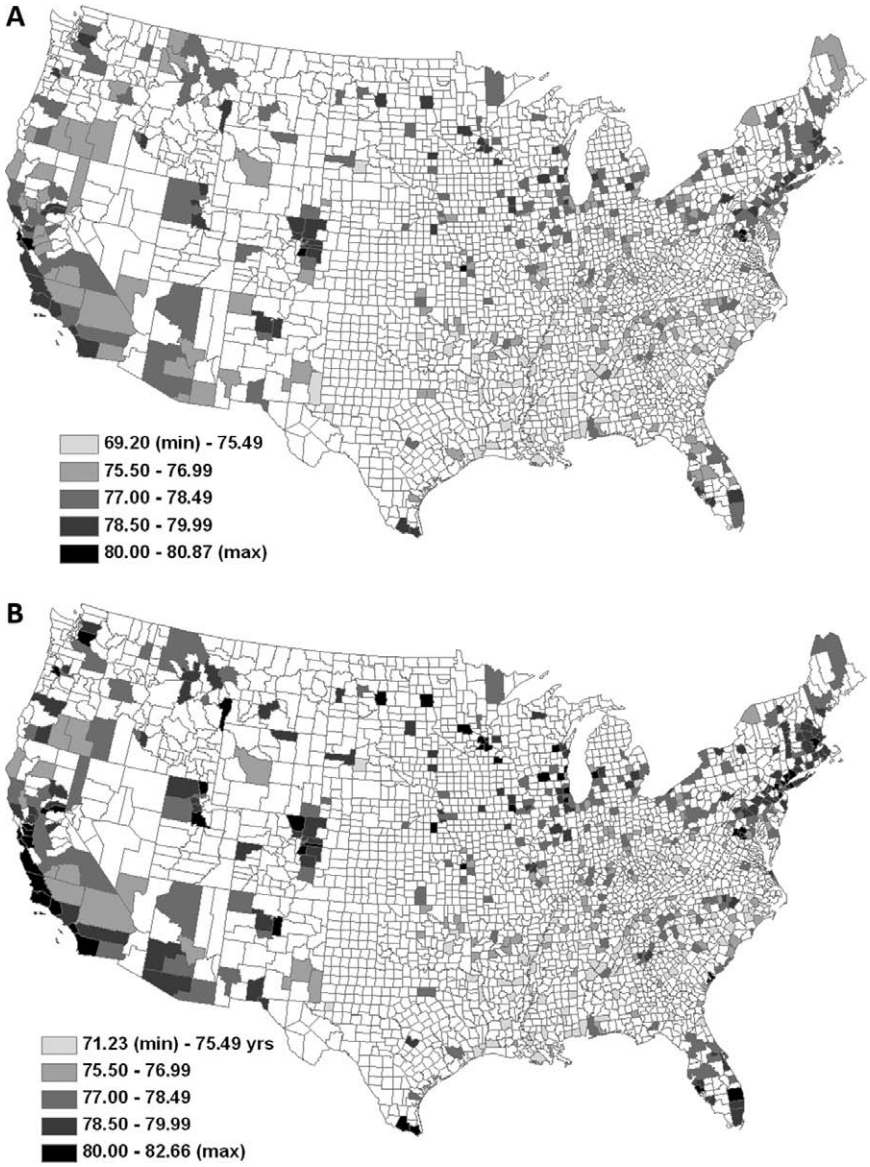

FIGURE 1. Map of United States with the 545 counties from data set 1 shaded according to (A) year 2000 and (B) year 2007 life expectancies.

$PM_{2.5}$ levels for each county were averaged across monitors within that county using a trimmed mean approach; those daily county-level means were further averaged across days to obtain a county-specific yearly $PM_{2.5}$ average.[29]

County-level life expectancies were calculated by applying a mixed-effects spatial Poisson model to mortality data from the National Center for Health Statistics (NCHS) and population data from the U.S. Census to obtain robust estimates of the number of deaths in each county.[30] These estimated counts were then used to calculate county life expectancies using standard life table techniques, which we discuss in more detail in the eAppendix (Section A, http://links.lww.com/EDE/A630).

Socioeconomic and demographic variables were obtained from the U.S. Census and the American Community Survey except per capita income, which was obtained from the Bureau of Economic Analysis. All yearly income variables were adjusted for inflation with 2000 as the base year. Age-standardized death rates for lung cancer and COPD were calculated using mortality data from NCHS using death rates for 2005 to serve as a proxy for 2007 (NCHS data for 2007 was not readily available). Last, data on smoking prevalence (proportion of the population who are current smokers) were available from the Behavioral Risk Factor Surveillance System in both 2000 and 2007 for 383 of the 545 counties.

Data set 2 included data for the year 1980 and the year 2000 for the same 211 U.S. counties included in the 51 metropolitan statistical areas (MSAs) previously analyzed by Pope and colleagues.[23] This data set is identical to that mentioned in the study by Pope et al,[23] where it is described in more detail.

Data set 3 extended data set 2 to 2007. All data were available at the county level except for $PM_{2.5}$, which for the year 1980 was available only at the MSA level and for the year 2007 was available at the county level for only 113 of the 211 counties originally included in the study by Pope et al.[23] Thus, for the year 2007, we assigned the same $PM_{2.5}$ values to all the counties that shared an MSA, consistent with the previous analysis.[23] Details and results pertaining to data sets 2 and 3 are summarized in the eAppendix (Section B1, http://links.lww.com/EDE/A630).

Statistical Analysis

Cross-sectional and first-difference linear regression models were fitted to all three data sets. Specifically, we regressed life expectancy versus $PM_{2.5}$ levels across counties separately for the years 1980 (data set 2), 2000 (data sets 1 and 2), and 2007 (data sets 1 and 3). We then regressed changes in life expectancy over the years 2000–2007 (data sets 1 and 3), 1980–2000 (data set 2), and 1980–2007 (data set 3) versus changes in $PM_{2.5}$ over those same periods adjusted for changes in the socioeconomic, demographic, and proxy smoking variables outlined above. Additionally for our largest data set (data set 1: 545 counties, 2000–2007), we performed several stratified and weighted analyses. More specifically, we estimated the effect of changes in $PM_{2.5}$ on life expectancy in models stratified by (1) percentage of the population with an urban residence in 2000; (2) population density in 2000; (3) land area in 2000; (4) $PM_{2.5}$ levels in 2000; (5) 5-year in-migration in 2000; and (6) change in average yearly temperature over the entire period. These stratified analyses allowed us to examine whether $PM_{2.5}$ effects on life expectancy were different in counties with particular demographic or weather characteristics. The sensitivity of our results to model specification was further assessed by fitting models weighted by (1) total population; (2) year 2000 population density; and (3) inverse land area. We included direct measures of the change in prevalence of smoking for the subgroup of counties with matching data on smoking prevalence (383 of 545), and fit separate models for men and women to determine whether effects differed by sex. To account for the correlation owing to clustering of counties in the same MSA, robust clustered standard errors were calculated for all models.[23,31] Specifically, the variance of the vector of estimated regression coefficients, β_{est}, is given by: $\mathrm{Var}(\beta_{est}) = (X^TX)^{-1}\ (X^TV_{est}X)\ (X^TX)^{-1}$, where V_{est} is a block-diagonal matrix with nonzero blocks $V_0,j = (y_j - \mu_{est},j)(y_j - \mu_{est},j)^T$, where j indexes the MSAs. β_{est} is equal to the ordinary least squares estimator. Models were estimated using either REGRESS in STATA version 11.0, lm() in R version 2.11.1, or PROC SURVEYREG in SAS, version 9.2.

RESULTS

We report the results of our primary analysis, which estimated the cross-sectional relation between life expectancy and $PM_{2.5}$, and between changes in life expectancy and changes in $PM_{2.5}$, for the period from 2000 to 2007 in 545 U.S. counties (data set 1). Results of the secondary analyses of the counties studied by Pope et al[23] using data sets 2 and 3 are shown in the eAppendix (Section B; eTables 1a, b and 2a, b, http://links.lww.com/EDE/A630). Table 1 lists the summary statistics for the variables in data set 1. In 2000, 189 of the 545 counties had a $PM_{2.5}$ level greater than the current 3-year NAAQS level of 15 $\mu g/m^3$; by 2007, only 48 of those 189 were not in compliance with the NAAQS. On average, $PM_{2.5}$ levels decreased at a rate of 0.22 $\mu g/m^3$ per year, a rate 33% lower than that observed in the 211 counties analyzed for the period 1980–2000 (0.33 $\mu g/m^3$ per year).[23]

Figure 2A, 2B shows life expectancies plotted against $PM_{2.5}$ levels for the years 2000 and 2007. Consistent with Pope et al,[23] cross-sectional regression models showed a negative association between life expectancy and $PM_{2.5}$ in both years. Details are summarized in the eAppendix (Section C, http://links.lww.com/EDE/A630).

Figure 2C, 2D show changes in life expectancy plotted against changes in $PM_{2.5}$ levels for 2000–2007. We also plotted the estimated regression lines under Models 1 and 3 of Table 2.

Table 2 summarizes estimated regression coefficients for the association between the changes in $PM_{2.5}$ and changes

TABLE 1. Summary Characteristics of the 545 Counties Analyzed for the Years 2000 and 2007

Variable	Mean (SD)
Life expectancy (years)	
2000	76.7 (1.7)
2007	77.5 (2.0)
Change	0.8 (0.6)
$PM_{2.5}$ ($\mu g/m^3$)	
2000	13.2 (3.4)
2007	11.6 (2.8)
Reduction	1.6 (1.5)
Per capita income (in thousands of $)	
2000	27.9 (7.4)
2007	30.4 (7.9)
Change	2.5 (2.3)
Population (in hundreds of thousands)	
2000	3.5 (6.3)
2007	3.8 (6.6)
Change	0.3 (0.6)
High-school graduates (proportion of population)	
2000	0.81 (0.07)
2007	0.85 (0.06)
Change	0.04 (0.02)
Black population (proportion of population)	
2000	0.115 (0.138)
2007	0.117 (0.139)
Change	0.002 (0.017)
Hispanic population (proportion of population)	
2000	0.119 (0.189)
2007	0.098 (0.135)
Change	−0.021 (0.057)
Deaths from lung cancer (no./10,000 population)[a]	
2000	16.4 (3.5)
2007	15.5 (3.8)
Change	−0.9 (2.2)
Deaths from COPD (no./10,000 population)[a]	
2000	12.8 (3.1)
2007	12.5 (3.5)
Change	−0.3 (2.1)

[a]2005 death rates are used as a proxy for 2007 death rates.

in life expectancy for 545 counties for the years 2000–2007 for selected regression models. When controlling for changes in all available socioeconomic and demographic variables as well as smoking prevalence proxy variables (model 3), a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ was associated with an estimated mean increase in life expectancy of 0.35 years (SE = 0.16 years, $P = 0.033$). The estimated effect of $PM_{2.5}$ on life expectancy was consistent across models adjusting for various patterns of potentially confounding variables (eg, models 2–4). Models 5–9 in Table 2 show the results for select stratified and weighted regressions. In counties with a population density >200 people per square mile, a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ was associated with an increased life expectancy of 0.72 (0.22 years, $P < 0.01$; model 6), when compared with −0.31 years (0.22 years, $P = 0.165$) in counties with <200 people per square mile (P difference < 0.01). In counties with proportion of urban residences >90%, a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ was associated with an increased life expectancy of 0.95 (0.31, $P < 0.01$; model 7), when compared with −0.16 (0.16 years, $P = 0.299$) in counties with <90% urban residences (P difference < 0.01).

When we reestimated model 3 of Table 2 using the square root of population density as the weight (model 8), the estimated effect of a 10 $\mu g/m^3$ reduction of $PM_{2.5}$ on life expectancy was more than double that observed in our unweighted analysis (0.74 [0.24] vs. 0.35 [0.16]). When that same model was weighted by the inverse of county land area (model 9), the effect was nearly triple that of the unweighted analysis (0.96 [0.27]). Additional details regarding stratified and weighted analyses are provided in eTables 3 and 4 of the eAppendix (http://links.lww.com/EDE/A630).

We conducted similar analyses for the data sets of 211 counties for the period from 1980 to 2007 and from 2000 to 2007, the results of which are presented in eTable 2a and b of the eAppendix (http://links.lww.com/EDE/A630), respectively. Results for the period from 1980 to 2000 were identical to those reported by Pope et al.[23]

Figure 3 summarizes the point estimate and 95% confidence interval for the effect of a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ on life expectancy for a select unweighted and unstratified regression model in each data set/time period. Models fitted using data sets 2 and 3 (left) controlled for changes in income, population, proportion of the population that is black, lung cancer death rate, and COPD death rate, corresponding to model 4 in eTable 2a and b (http://links.lww.com/EDE/A630). Models fitted using data set 1 controlled for all available variables and corresponded to model 3 in Table 2. These estimates were fairly consistent, though estimates corresponding to the counties from Pope et al[23] for the period 2000–2007 appeared slightly larger than those from other analyses.

In the analyses stratified by sex, the estimated effect of a 10 $\mu g/m^3$ reduction in $PM_{2.5}$ for the covariate pattern corresponding to model 3 of Table 2 was an additional 0.59 (0.17) years of life expectancy for women and 0.08 (0.20) years for men (P difference = 0.027). Differences by sex were also observed in stratified and weighted models, although with less precision. Sex differences were smaller in the most urban counties (urban rate > 90%). Similar results were observed for the period from 1980 to 2000 in data set 2. (Sex-specific results are presented in eTable 5, http://links.lww.com/EDE/A630.)

Effect estimates were not highly sensitive to the inclusion of the estimated change in smoking prevalence. Table 3 summarizes the results for the inclusion/exclusion of the smoking prevalence variable across several models. For example, when model 3 in Table 2 was reestimated for the 383

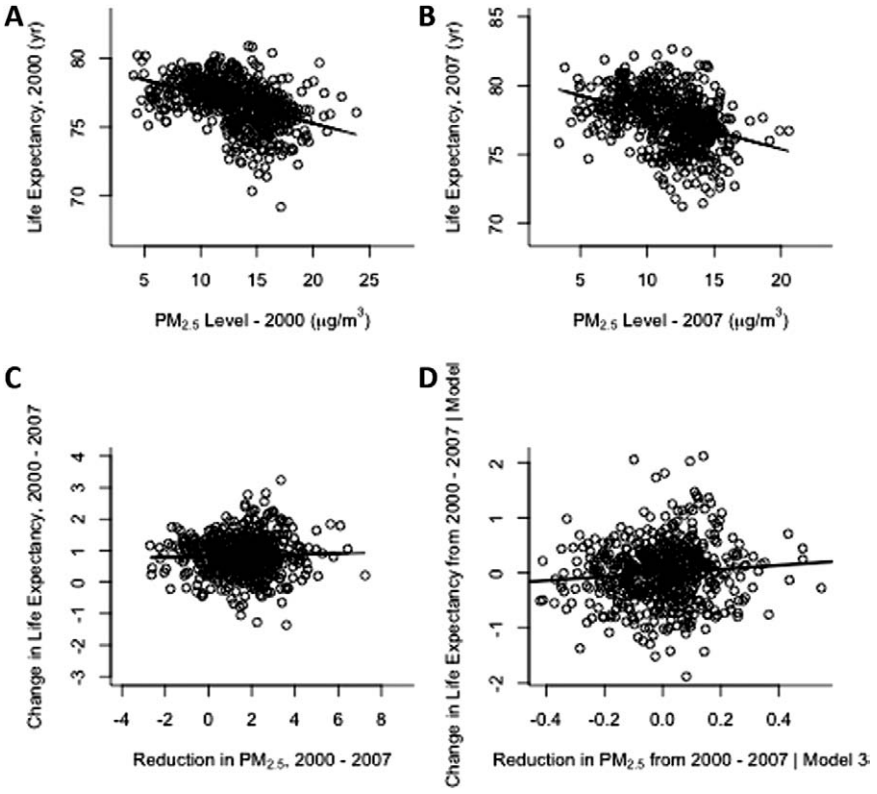

FIGURE 2. Cross-sectional life expectancies plotted versus $PM_{2.5}$ levels for (A) 2000 and (B) 2007 in data set 1. The slopes of the regression lines correspond to estimates from the simple model: LE = intercept + slope × $PM_{2.5}$ in both the 2000 and 2007 plots. C, On the left, the data are plotted as change in life expectancy versus change in $PM_{2.5}$ over the period 2000–2007. The regression line corresponds to the simple model ΔLE = intercept + slope × $\Delta PM_{2.5}$ (model 1 in Table 2). D, On the right is the added variable plot for $PM_{2.5}$ corresponding to model 3 in Table 2.

counties with matching smoking prevalence data, a reduction of 10 $\mu g/m^3$ was associated with an increase in life expectancy of 0.49 (0.19) years without including change in smoking prevalence in the model, and 0.47 (0.19) years when including those changes. Similar results for smoking were observed in our stratified and weighted models, as well as in our models for men and women separately.

DISCUSSION

Data on air pollution and life expectancy from 545 U.S. counties in 2000 and 2007 show that recent declines in $PM_{2.5}$ to relatively low levels continue to prolong life expectancy in the United States. These benefits are largest among the most urban and densely populated counties. These associations were estimated controlling for socioeconomic and demographic variables as well proxy variables for and direct measures of smoking prevalence.

In previous studies, a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ has been associated with gains from 0.42 to 1.51 years of life expectancy.[22,23] Here, a decrease of 10 $\mu g/m^3$ in $PM_{2.5}$ was associated with an increase in life expectancy of 0.35 (0.16) years for 545 counties for the period from 2000 to 2007. An increase in life expectancy of 0.56 (0.19) years was estimated for the same 211 counties included in the analysis of Pope et al[23] but extended to the period 1980–2007. The estimated effect in those 211 counties from 2000 to 2007 was equal to 1.00 (0.32). Stratified and weighted analyses within the 545 counties from 2000 to 2007 yielded larger estimates between 0.72 (0.22) and 1.12 (0.32) years—broadly in agreement with those previously reported.

From 2000 to 2007, the average increase in life expectancy across the counties in this study was 0.84 years, and the average decrease in $PM_{2.5}$ in those same counties was 1.56 $\mu g/m^3$. Although $PM_{2.5}$ reductions presumably account for some of the improvements in life expectancy over this period, it is only one of many contributing factors. Other factors may include improvements in the prevention and control of the chronic diseases of adulthood, particularly cardiovascular diseases (CVD) and stroke,[32,33] and changes in the risk factors associated with them, including medical advances, declines in smoking, and decreases in blood pressure and cholesterol.[33] Considering the well-established link between air pollution and CVD mortality,[5,7,8] and changes in other CVD risk factors, issues of multicausality and competing risk make it difficult to quantify exactly the changes in life expectancy attributable to reductions in $PM_{2.5}$. However, if we consider one of our more conservative effect estimates (model 3, Table 2), the 1.56 $\mu g/m^3$ reduction in $PM_{2.5}$ accounts for about 0.055 years (1.56 × 0.035) of additional life expectancy or roughly 7% of the increase in life expectancy. Using the estimate from our most urban counties (model 7, Table 2), the increase in life expectancy attributable to the average reduction in $PM_{2.5}$ was 0.148 years (1.56 × 0.095) or as much as 18% of the total increase.

An interesting aspect of this study was how pronounced the $PM_{2.5}$ effect was for the original 211 counties from 2000 to 2007. Considering that they were originally selected simply

TABLE 2. Results of Selected Regression Models for County-Level Analysis, 2000–2007

Variable	Model 1	Model 2	Model 3	Model 4	Model 5[a]	Model 6[b]	Model 7[c]	Model 8[d]	Model 9[e]
No. of county units	(n = 545)	(n = 545)	(n = 545)	(n = 545)	(n = 257)	(n = 307)	(n = 169)	(n = 545)	(n = 545)
Intercept	0.82 (0.04)	1.08 (0.08)	1.00 (0.08)	1.03 (0.07)	0.97 (0.10)	0.91 (0.11)	0.84 (0.15)	0.79 (0.15)	0.67 (0.15)
Reduction in $PM_{2.5}$ (10 $\mu g/m^3$)	0.14 (0.19)	0.35 (0.17)	0.35 (0.16)	0.34 (0.16)	0.30 (0.23)	0.72 (0.22)	0.95 (0.31)	0.74 (0.24)	0.96 (0.28)
Change in income (in thousands of $)	—	0.013 (0.017)	0.017 (0.018)	—	0.005 (0.018)	0.02 (0.02)	−0.01 (0.03)	0.03 (0.02)	0.05 (0.02)
Change in population (in hundreds of thousands)	—	0.13 (0.05)	0.11 (0.05)	0.11 (0.04)	0.07 (0.05)	0.06 (0.04)	0.02 (0.04)	0.07 (0.06)	0.34 (0.12)
Change in high-school graduates (proportion of population)	—	−9.12 (1.61)	−7.98 (1.56)	−7.83 (1.57)	−7.27 (1.95)	−4.42 (2.60)	4.04 (3.20)	−1.94 (3.35)	−3.30 (3.45)
Change in black population (proportion of population)	—	−6.55 (2.05)	−6.34 (1.97)	−6.43 (2.00)	−7.86 (3.07)	−9.02 (2.27)	−12.56 (3.59)	−11.14 (3.00)	−6.21 (2.97)
Change in Hispanic population (proportion of population)	—	−2.16 (0.47)	−2.03 (0.47)	−2.13 (0.49)	−2.12 (0.59)	−2.46 (0.68)	−0.95 (0.62)	−3.25 (0.63)	−4.57 (0.75)
Change in lung cancer mortality rate (no./10,000 population)	—	—	−0.02 (0.02)	−0.02 (0.02)	−0.02 (0.02)	−0.05 (0.03)	−0.05 (0.05)	−0.07 (0.02)	−0.07 (0.03)
Change in COPD mortality rate (no./10,000 population)	—	—	−0.05 (0.01)	−0.05 (0.02)	−0.05 (0.02)	−0.06 (0.03)	−0.06 (0.05)	−0.08 (0.02)	−0.06 (0.02)

Regression coefficients (SE).
[a]Included only counties with the largest year 2000 population in the MSA.
[b]Included only counties with a year 2000 population density >200 people per square mile mile.
[c]Included only counties with a year 2000 urban rate >90%.
[d]Weighted by the square root of the year 2000 population density.
[e]Weighted by the inverse of county land area.

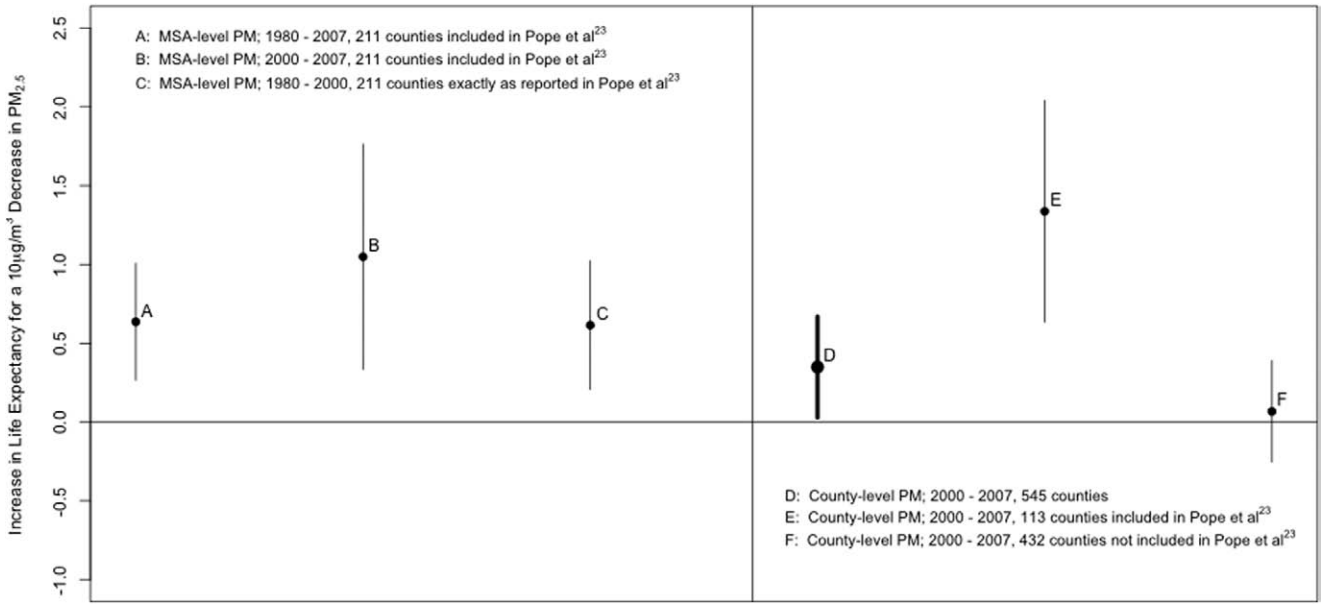

FIGURE 3. Point estimates (circles) and 95% confidence intervals (vertical lines) for the effect of a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ on life expectancy. Estimates A and B were obtained from data set 3; estimate C was obtained from data set 2. Estimates A, B, and C were adjusted for changes in income, population, proportion of the population that is black, lung cancer death rate, and COPD death rate (model 4, eTable 2a, b, http://links.lww.com/EDE/A630). Estimates D, E, and F were obtained from data set 1, adjusted for changes in income, population, proportion of high-school graduates, proportion of the population that is black, proportion of the population that is Hispanic, lung cancer death rate, and COPD death rate (model 3, Table 2).

TABLE 3. Comparison of Results of Selected Models for Inclusion of Smoking Variable Versus No Inclusion of Smoking Variable

Selected Counties and Analysis	No. Counties	Full Model,[a] With Smoking β (SE; P) for 10 $\mu g/m^3$ $PM_{2.5}$	Full Model,[a] Without Smoking β (SE; P) for 10 $\mu g/m^3$ $PM_{2.5}$
All counties	383	0.47 (0.19; 0.013)	0.49 (0.19; 0.011)
2000 population density (persons per square mile)			
>800	110	0.52 (0.43; 0.230)	0.53 (0.43; 0.221)
>600	139	0.68 (0.30; 0.028)	0.68 (0.30; 0.027)
>400	187	0.71 (0.26; 0.007)	0.70 (0.25; 0.007)
>200	272	0.67 (0.22; 0.003)	0.65 (0.22; 0.004)
<200	111	−0.50 (0.30; 0.100)	−0.39 (0.30; 0.193)
2000 urban rate			
>90%	157	0.76 (0.28; 0.009)	0.76 (0.28; 0.008)
>95%	101	1.01 (0.31; 0.002)	0.98 (0.32; 0.003)
<90%	226	−0.14 (0.20; 0.483)	−0.13 (0.20; 0.513)
2000 population density and 2000 urban rate			
>200 >90%	100	0.95 (0.32; 0.004)	0.93 (0.32; 0.005)
Regression weighted by square root of 2000 population density (all counties)	383	0.77 (0.24; 0.002)	0.76 (0.25; 0.003)
Regression weighted by inverse of county land area (all counties)	383	0.81 (0.26; 0.002)	0.74 (0.27; 0.007)
Sex			
Men	383	0.20 (0.23; 0.389)	0.22 (0.23; 0.343)
Women	383	0.71 (0.20; 0.001)	0.72 (0.20; <0.001)

[a]Covariates include change in income, change in population, change in high-school graduates, change in proportion of black population, change in proportion of Hispanic population, change in lung cancer mortality rate, and change in COPD mortality rate. Analysis used were SAS 9.2, PROC SURVEYREG, clustered by MSA, using the "weight" statement, and STATA 11.0, REGRESS.

on the availability of matching pollution data, what is special about these counties that results in larger estimates of the effect of $PM_{2.5}$ on life expectancy? The stratified and weighted analyses suggest plausible explanations. For instance, the 211 counties were all in metropolitan areas, and the stratified analyses suggest that the effect of $PM_{2.5}$ on life expectancy is greatest in the most urban counties. One possible reason is that the composition of $PM_{2.5}$ is different in urban areas[34] causing $PM_{2.5}$ to have a larger health impact. Another possibility is the "nonmetropolitan mortality penalty"—the recent phenomenon in which mortality rates are higher in rural when compared with urban areas.[35] Although it is not clear why the mortality gap between metro and nonmetro areas has widened, some hypotheses include greater improvements in standards of care in metro areas, changes in uninsurance rates, changes in disease incidence, and changes in health behaviors.[35] These, however, would be valid explanations only if they occurred at different rates in metropolitan areas when compared with rural areas. If so, then perhaps failure to include variables that captured one or more of these differences could explain the different estimates of the effect of $PM_{2.5}$ on life expectancy.

Alternatively, metropolitan areas are more densely populated than nonmetro areas. Our models that stratified by population density showed that the effect of $PM_{2.5}$ on life expectancy is greatest in the most densely populated study areas (those with a population density of at least 200 people per square mile)—possibly suggesting a role for differential exposure misclassification. That is, in densely populated areas, it is more likely that any two people from the same area are exposed to the same level of $PM_{2.5}$ with perhaps less exposure misclassification. This possibility was supported in our models weighted by the square root of population density and the inverse of land area, which placed more weight on the most densely populated counties and the smallest counties. In these models, the effect of a 10 $\mu g/m^3$ decrease in $PM_{2.5}$ on life expectancy was much larger than the equivalent unweighted analysis.

Another interesting finding was the difference in the effect of changes in $PM_{2.5}$ on men and women. Findings in the literature regarding the effects of air pollution by sex for long-term exposure have been mixed. Studies using the American Cancer Society and Harvard Six Cities cohorts show no significant difference in pollution-related mortality between men and women.[4–8,10] Studies using a Medicare cohort have reported different effects by age and region, but did not stratify by sex.[28,36,37] In a study using the Adventist Health cohort, Chen et al[38] reported a large effect of $PM_{2.5}$ on fatal coronary heart disease in women but no association in men. Similarly, in separate studies, Lipsett et al,[39] using a cohort of women (California Teachers' Study), reported associations between particulate matter and cardiovascular mortality, while Puett et al,[40] using a cohort of men (Male Health Professionals), found no association with all-cause mortality or fatal coronary heart disease. For

our main analysis using all 545 counties, we find a larger effect of $PM_{2.5}$ on women, suggesting that reductions in $PM_{2.5}$ are more beneficial to gains in life expectancy for women. Models fitted using data for the period from 1980 to 2000 as mentioned in Pope et al[23] showed similar results. Future studies should investigate more thoroughly the possibility of different $PM_{2.5}$-mortality associations for men versus women.

One factor that appeared to play no role in the $PM_{2.5}$ and life expectancy relation, however, was baseline $PM_{2.5}$ level. This is in agreement with the findings by Pope et al,[23] and implies that, although we may see differences across levels of population density, urban rate, and land area, this is not attributable to these areas having a higher or lower baseline $PM_{2.5}$ level. Furthermore, this finding suggests that there is no clear threshold below which further reductions in $PM_{2.5}$ levels provide no benefit (eAppendix, eTable 3, http://links.lww.com/EDE/A630). The fact that our results were not sensitive to the inclusion of direct measures of change in smoking prevalence suggests that the estimated gains in life expectancy for a 10 $\mu g/m^3$ reduction in $PM_{2.5}$ are not a result of confounding attributable to changes in smoking prevalence.

Unlike previous cross-sectional analyses,[16,17] we were able to estimate the association between county-specific temporal changes in $PM_{2.5}$ levels and county-specific temporal changes on life expectancy adjusted by temporal changes in several potential confounding factors. By looking at within-county temporal changes, we reduce the potential bias owing to unmeasured confounding. Furthermore, by estimating clustered robust standard errors at the MSA level, we took a conservative approach in accounting for potential spatial correlation between neighboring counties.

Our analysis has the strengths of using some of the largest available data sets, and applying relatively simple analyses. Additionally, we improved on the original analysis by constructing a data set with $PM_{2.5}$ measured at the county level, in contrast to the more coarse MSA-level readings used in previous studies.[7,23]

The analysis is limited, however, in its ability to control for all potential unmeasured confounding. Additionally, in comparing selected years, we do not fully exploit potentially informative data between those years. Furthermore, sophisticated analyses of the U.S. Medicare population by Greven et al[36] did not observe associations between "local" trends in $PM_{2.5}$ levels and "local" trends in mortality in 814 zip code level locations in the United States for the period from 2000 to 2006. "Local" trends were defined as the difference between monitor-specific trends and national trends. The Medicare cohorts, however, consisted only of people age 65 years and older, whereas our life expectancy calculations integrate over all ages. Also, other studies using Medicare-based cohorts have found significant associations between $PM_{2.5}$ and overall mortality.[28,37] Future studies are needed to investigate whether these differences among studies are attributable to differences in statistical models, data sources, or populations studied.

It is also worth considering whether life expectancy was the most appropriate outcome to consider in our model. Because life expectancies are calculated from age-specific mortality rates, perhaps a model with age-specific mortality rates as the outcome would be more appropriate, allowing the age groups most affected by $PM_{2.5}$ exposure to be pinpointed precisely.

In summary, our study reports strong evidence of an association between recent further reductions in fine particulate air pollution and improvements in life expectancy in the United States, especially in densely populated urban areas.

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