

What Caused Racial Disparities in Particulate Exposure to Fall? New Evidence from the Clean Air Act and Satellite-Based Measures of Air Quality[†]

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This project links administrative census microdata to spatially continuous measures of particulate pollution (PM_{2.5}) to first document and then decompose the key drivers of convergence in black-white pollution exposure differences. We use quantile regression to show that a significant portion of the convergence in Black-White exposure is attributable to differential impacts of the Clean Air Act (CAA) in Black and White communities. Areas with larger Black populations saw greater CAA-related declines in PM_{2.5}. We show that the CAA can account for over 60 percent of the racial convergence in PM_{2.5} pollution exposure in the United States since 2000. (JEL J15, K32, Q51, Q53, Q58)

Landmark studies in the 1980s (see for example GAO 1983; Chavis and Lee 1987) demonstrated that low income and/or racial minorities in the United States are more likely to be exposed to environmental burdens. This issue had become so politically important by the 1990s that President Clinton issued Executive Order 12898 in 1994, which ordered the US Environmental Protection Agency (EPA) to explicitly study this “environmental justice” question.¹ However, despite its large volume, the existing evidence about racial disparities in pollution exposure is largely piecemeal and indirect.

The evidence is *piecemeal* because pollution monitoring networks are sparse. For example, less than 20 percent of US counties contain a regulatory grade device

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¹Banzhaf, Ma, and Timmins (2019) have an excellent recent review of the economics literature on this subject.

capable of monitoring small particulates (Fowlie, Rubin, and Walker 2019).² The evidence remains somewhat *indirect* because researchers have been forced to use proxies for potential exposure such as distance to a polluting facility.³ Distance to a facility is an imperfect substitute for ambient air pollution exposure, both for reasons related to air transport and because mobile sources of pollution are also important contributors to local air quality. Hence, while we know that there are racial differences in the proximity to toxic facilities and hazardous waste sites, it is less clear how these differences translate into differences in measured exposures. Moreover, we know very little about why racial gaps in pollution exposure may have changed over time.

This paper addresses these gaps in our knowledge using newly available national data on PM_{2.5} exposure from 2000 to 2015. Advances in remote sensing technology combined with machine learning prediction tools have allowed researchers to combine data from satellite imagery, pollution monitors, land use characteristics and chemical air transport models to generate fine-grained (one kilometer grid) measures of ambient air pollution levels for the entire United States (Di et al. 2016a, b; van Donkelaar et al. 2016). We merge these granular pollution data to individual survey responses from restricted versions of the 2000 census and the 2001–2015 American Community Survey (ACS) at the census block level.

The paper proceeds in four parts. We first use these data to document gaps in ambient exposure to PM_{2.5} between African Americans and non-Hispanic Whites and to show how these gaps changed over time from 2000 to 2015. Next, we explore whether these cross-sectional gaps in pollution exposure can be explained by differences in individual and/or neighborhood characteristics, as reported in the census or ACS. Third, we explore the extent to which changes in relative mobility versus relative improvements in neighborhood air quality have contributed to the changes in gaps in pollution exposure over this time period. Lastly, we use quantile regression methods proposed by Firpo, Fortin, and Lemieux (2009) to explore the extent to which the spatially targeted nature of the CAA, and associated introduction of the PM_{2.5} National Ambient Air Quality Standards (NAAQS), has affected different parts of the national pollution distribution and, in turn, the observed Black-White pollution gap in the United States.

The analysis confirms that African Americans tend to live in the most polluted areas nationally. However, this Black-White gap in mean pollution exposure has closed substantially since the turn of the century. The mean gap in pollution exposure

²Similarly, Hsiang, Oliva, and Walker (2019) point out that out of 3,144 counties, only 1,289 have monitors for any “criteria” air pollutant (i.e., pollutants regulated under the CAA) at any point between 1990 and 2015.

³For example, several case studies on residential proximity to polluting industrial facilities find that racial and ethnicity minority groups and/or lower socioeconomic status groups experienced closer average proximity to industrial facilities compared with other groups, and that this pattern persists over time, e.g., Abel and White (2011) who study Seattle, 1990 to 2007; Hipp and Lakon (2010) who study southern California, 1990 to 2000; Pais, Crowder, and Downey (2013) who examine a national cohort from 1990 to 2007. There are challenges to drawing causal inferences from this literature ranging from ecological fallacy (Depro, Timmins, and O’Neil 2015; Hsiang, Oliva, and Walker 2019) to problems associated with assuming that people in geographic areas that do not contain hazards are not exposed to pollutants, even when the hazards in question may lie close to geographic boundaries (Banzhaf, Ma, and Timmins 2019; Mohai and Saha 2006; Mohai, Pellow, and Roberts 2009). Currie (2011) looks at all births in five large states between 1989 and 2003 and shows that pregnant Black women are about 50 percent more likely to live within 2,000 meters of a toxic release inventory site and 100 percent more likely to live within 2,000 meters of a superfund site than pregnant White women.

has converged from 1.5 micrograms per cubic meter ($\mu\text{g per m}^3$) in 2000 to only 0.5 $\mu\text{g/m}^3$ in 2015. This convergence alone could potentially account for almost 5 percent of the improvement in relative life expectancy between Black and White Americans over this time period.⁴ We then explore the underlying cross-sectional correlates of the observed pollution gaps by leveraging the individual microdata in the census and ACS. We begin by comparing the unconditional mean gap in pollution exposure between African Americans and non-Hispanic Whites to the conditional mean pollution gap after controlling for individual characteristics (e.g., income, education, household structure).⁵ We also examine whether individual characteristics are able to explain gaps in exposure at other quantiles of the pollution distribution, in the spirit of DiNardo, Fortin, and Lemieux (1996). We find that virtually none of the racial difference in exposure can be explained by differences in individual or household-level characteristics such as income, suggesting that only a small portion of the observed convergence in pollution levels can be explained by relative changes in these characteristics over time.

Mechanically, there are two remaining ways this narrowing of the pollution gap could have occurred: areas with relatively large shares of African Americans may have enjoyed larger pollution reductions than other areas, or relative population shares could have shifted in ways that benefited African Americans relative to the non-Hispanic White population. We use a simple decomposition to show that relative mobility differences or changes in Black-White population shares are not able to explain the observed convergence in pollution exposure. While the White population has been gradually shifting to more urban and hence more polluted areas, this phenomenon explains very little of the observed Black-White convergence in pollution exposure when compared to the large and significant air quality improvements in the average Black neighborhood over this time period.

The convergence in the racial gap in pollution exposure between 2000 and 2015 can be entirely accounted for by the fact that areas with larger shares of African American residents showed the greatest improvement in air quality over this time period. Why is this the case? We show that much of this improvement is driven by the introduction of the PM2.5 NAAQS, which greatly improved air quality in newly regulated areas—areas with higher concentrations of African Americans. More specifically, we use unconditional quantile regression (Firpo, Fortin, and Lemieux 2009) in a difference-in-difference setting to show how the introduction of the PM2.5 NAAQS affected different quantiles of the national pollution distribution. We then combine these quantile regression estimates with the Black and White population shares in the respective pollution quantiles to calculate that over 60 percent of the observed convergence in mean PM2.5 differences between Black and White Americans over this time period can be traced back to the spatially targeted nature of the CAA regulations.

This is the first paper, to our knowledge, that links nationally representative, individual-level survey data to a national surface grid of PM2.5 pollution measurements to explore cross-sectional differences and trends in environmental inequality

⁴See Section I below for a more complete description of this calculation.

⁵Throughout the paper, we use the term “conditional mean pollution gap” to reflect the difference left after adjusting (i.e., conditioning) for differences in covariates. Formally, these gaps measure the average of the conditional differences that exist for each value of the covariates.

between racial groups.⁶ Moreover, we are not aware of any papers that have explored the causal determinants of narrowing pollution gaps between racial groups over time.⁷ Our data not only have useful features from a measurement perspective, allowing for higher quality measurement of the distribution of pollution exposure than has been possible before, but they also allow us to answer questions that cannot be addressed with public-use census data. For example, the restricted versions of the census and ACS data (which provide block-level geographic information) allow us to distinguish between differences in pollution exposure that can be explained by differences in individual characteristics (e.g., income) or differences in neighborhood characteristics (e.g., average years of schooling). While these findings are descriptive, we are able to explore, for the first time, how much variation in pollution exposure might plausibly be explained by individual endowments, and how much may instead be explained by aggregate, neighborhood-level characteristics. Lastly, the spatially continuous PM_{2.5} measurements allow us to create these statistics and perform these decompositions for the entire continental United States, as opposed to focusing on a single city or on communities that are proximate to a toxic plant or a pollution monitor.

The second contribution of this paper is to explore the distributional effects of environmental policy and the CAA more specifically. While a substantial literature examines the average effects of the CAA on pollution exposure and the harms that it causes (e.g., Chay and Greenstone 2003; Isen, Rossin-Slater, and Walker 2017), we know of no other work that explores the impact of the CAA on different empirical moments of the nationwide pollution distribution. For example, we are able to address the question of how much the CAA NAAQS have compressed the national pollution distribution, and to ask which quantiles show the largest effects? The advent of unconditional quantile regression and related methods (Firpo, Fortin, and Lemieux 2009), combined with the new availability of spatially continuous PM_{2.5} measurements, make such analysis possible.

In summary, our study uses high-resolution PM_{2.5} data and restricted-access census data to measure gaps in racial exposure to pollution for a nationally representative sample of the US population. Our main innovation is to explore the reasons why the racial gap has declined by asking what part of the decline can be

⁶A small but growing literature has begun using remote sensing data to measure the distribution of environmental hazards (see e.g., Fowlie, Rubin, and Walker 2019 for a recent overview and application). A subset of this literature studies environmental inequality by merging remote-sensing data to census tract or census block group demographic data. For example, Clark, Millet, and Marshall (2014, 2017) examine racial differences in exposure to nitrogen oxide using 2006 census block-group nitrogen oxide measurements linked to the 2000 decennial census data, and Voorheis (2017) examines differences in exposure to nitrogen oxide and PM_{2.5} using satellite data combined with tract-level aggregates from the ACS.

⁷Relatively few US studies have explored temporal trends in racial gaps in ambient air pollution or transportation-related air pollution. Brajer and Hall (2005), studied ozone and coarse particulate matter in Southern California from 1990 to 1999, and found that on average, as air pollution decreased over time, Asians and Hispanics experienced larger reductions in ozone concentrations but smaller reductions in coarse particulate matter concentrations, compared with other groups. Kravitz-Wirtz et al. (2016) studied nitrogen dioxide and particulate matter exposures in the United States for a cohort of 9,000 families from 1990 to 2009, and found that though exposures decreased over time, they remained higher for Blacks and Hispanics than for Whites. Ard (2015) looks at racial trends in exposures to toxic releases from 1995 to 2004, using data on releases of 415 chemicals from 17,604 facilities reporting in the Toxic Release Inventory. She finds that potential exposure to toxics declined for all, but that African Americans are still more exposed than Whites or Hispanics, even conditional on income and education. Voorheis (2017) uses administrative records and satellite data to compare within-person changes in pollution exposure between Black and White Americans.

attributed to convergence in the individual and household-level characteristics of African American and other households, how much can be explained by the relative mobility of different racial groups (e.g., Black people moving away from polluted areas), how much can be explained by more rapid clean-up of historically Black neighborhoods; and how much of the more rapid cleanup of historically Black neighborhoods that we observe is due to the spatially targeted enforcement of the CAA.

The rest of the paper proceeds as follows. Section I introduces the linked census and satellite derived pollution data and provides initial descriptive statistics on environmental inequality between racial groups. Section II explores whether these mean and quantile differences can be explained by differences in individual characteristics and changes to those characteristics over time. Section III tests for how the spatially targeted nature of the CAA affects the national distribution of PM_{2.5} exposure, and how these quantile changes map into the observed Black-White gap in pollution exposure. Section IV concludes.

I. Data and Descriptive Statistics on Racial Gaps in Pollution Exposure

Environmental science has seen a recent explosion of research combining spatially continuous satellite measurements of pollution correlates (e.g., aerosol optical depth) with other observable pollution correlates such as emissions inventories, chemical transport models, land use characteristics, and weather patterns (see e.g., Di et al. 2016a,b; van Donkelaar et al. 2016). The basic idea is to build a predictive model of a pollutant of interest (e.g., PM_{2.5}) by correlating in situ EPA monitor data with the observable predictors of air pollution measures using modern model selection techniques (e.g., cross-validated neural nets). Researchers then use these models to predict air pollution “out of sample” for the large segments of the United States without existing pollution monitors but with satellite measurements. We use data from Di et al. (2016a,b), who produce daily PM_{2.5} concentrations at a 0.01 degree by 0.01 degree resolution (one kilometer by one kilometer at the equator) for the contiguous United States from 2000 to 2015.^{8,9} We spatially intersect this gridded, raster data with census block boundary files from the 2000 and 2010 censuses, which we use to merge the pollution data to the individual survey responses from the 2000 census and 2001–2015 ACS.

It is important to note that these pollution data are estimates of ground-level pollution concentrations. These estimates perform well—on average, they match the “ground truth” as measured by EPA monitors, with very high, in-sample measures of fit. However, there is some evidence that these satellite-derived measures may deviate from the ground truth at the tails of the pollution exposure distribution. Fowlie, Rubin, and Walker (2019) show that two of the most commonly used measures, Di et al. (2016a,b) and van Donkelaar et al. (2016), are biased downward for high PM_{2.5} levels. It seems likely in our setting than these prediction errors will

⁸The published version of Di et al. (2016a,b) use data from 2000 to 2012. We received years 2013–2015 via direct correspondence with the authors.

⁹We have replicated most of the results in this project using similar data from van Donkelaar et al. (2016), and the qualitative conclusions are very similar.

attenuate measured disparities since African Americans are more likely than Whites to be located in the most highly polluted places. We will proceed with our analyses treating the satellite data as if it were the truth, keeping in mind the caveat that our results may be a lower bound on true racial gaps in exposure.

We merge the pollution data with individual-level data from the 2000 census long form (one in six US households) (US Census Bureau 2010) and from the 2001–2015 ACS (US Census Bureau 2015) using household census block locations. Our primary comparisons focus on the non-Hispanic White and African American populations. We focus on gaps between African Americans and non-Hispanic Whites because historically these have been the largest and most well-documented gaps. Additionally, there are potential measurement issues in studying differences between Hispanics and non-Hispanic Whites over time. For example, studies which have linked individual responses to the 2000 and 2010 decennial censuses find evidence that Hispanic identity is more fluid over time than White or Black racial identities (Liebler et al. 2017).

Figure 1 plots mean pollution exposure for both the African American (dotted red line) and non-Hispanic White population (solid blue line) from 2000 to 2015. The observed Black-White gap in mean pollution exposure was $1.6 \mu\text{g}/\text{m}^3$ in 2000, narrowing to $0.54 \mu\text{g}/\text{m}^3$ in 2015. Although African American exposure fell more, it was higher to begin with, so that the percentage reduction is similar for both Black and White people. However, since the level of pollution exposure is important, that is our main focus. One way to interpret the differences in levels is to translate the gaps into racial differences in life expectancy through the lens of a PM2.5 concentration-mortality response function. Pope, Ezzati, and Dockery (2009) estimate that life expectancy is reduced by 0.61 years for each $10 \mu\text{g}/\text{m}^3$ increase in sustained exposure to PM2.5. Over this time period, the Black-White gap in life expectancy fell from about 5 years to 3.5 years (Arias, Xu, and Kochanek 2019). Thus, the observed $1 \mu\text{g}/\text{m}^3$ improvement in the Black-White pollution gap could potentially explain 4 percent of this improvement in the Black-White mortality gap.¹⁰

Do these national gaps in pollution exposure exist at other geographic scales? The national gaps in pollution exposure reflect both differences in where Black and White people live and within-area gaps in pollution exposure. For example, the average, within-state differences in pollution exposure could be the same as the nationwide differences, or the within-state gaps in pollution exposure could be minimal indicating that African Americans simply live in more polluted states on average. Online Appendix Figure B1 explores average, within-area gaps in exposure at different geographic scales. We regress the pollution exposure of an individual on an indicator for whether or not that individual is African American, controlling for different sets of geographic fixed effects. The red, hollow squares represent the conditional mean difference in pollution exposure between African Americans and non-Hispanic White individuals after controlling for state fixed effects. These within-state differences in exposure are smaller than the national mean differences

¹⁰This is calculated as $0.61 \times (1/10)/1.5$ years. Note that Arias, Xu, and Kochanek (2019) only report Black-White gaps in life expectancy as far back as 2006. The 2000–2015 change in the Black-White life expectancy was likely larger than 1.5, reducing the percentage contribution of PM2.5 in explaining this improvement.

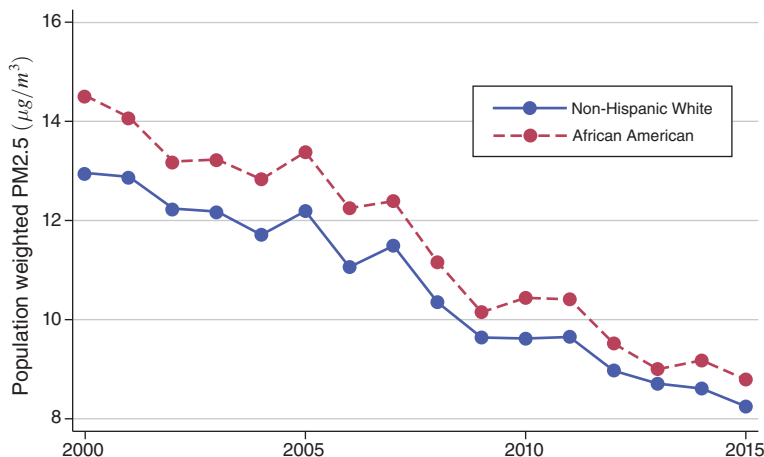


FIGURE 1. TRENDS IN POLLUTION EXPOSURE BY RACE

Note: This figure plots mean PM_{2.5} exposure by year, separately for African Americans and the non-Hispanic White population.

Sources: US Census Bureau (2010, 2015) and Di et al. (2016a,b)

in exposure, and they exhibit a flatter downward trend. The average within-county differences are smaller, and the within-tract differences in exposure are essentially zero. For example, in 2000, the average within-tract gap was only $0.012 \mu\text{g}/\text{m}^3$. In 2000, the unconditional, nationwide gap was $1.5 \mu\text{g}/\text{m}^3$, suggesting that more than 99 percent of the national gap ($1 - 0.012/1.542$) is driven by differences in the census tracts where White and Black people live rather than by White and Black differences in exposure within the average census tract. Online Appendix Table B1 shows the adjusted R^2 s from these regressions, indicating that almost all of the variation in individual exposures is explained by census-tract fixed effects. Since the median census tract is five square kilometers, our one kilometer by one kilometer grid of pollution measures is arguably fine enough to detect within census-tract differences in exposure. However, the calculations in this section suggest that these differences are negligible.

While Figure 1 and online Appendix Figure B1 present the mean and conditional mean Black-White gap over time, the data also allow us to explore the entire distribution of pollution exposure for each race group and how these distributions have changed over time. Figure 2 plots the pollution densities, separately for the African American and non-Hispanic White population in both 2000 and 2015.¹¹ When comparing the x -axis of both the 2000 and 2015 figures, it becomes clear that PM_{2.5} pollution levels have fallen dramatically for both groups. For example, in 2000, the bulk of both distributions lies above $10 \mu\text{g}/\text{m}^3$, while in 2015 the bulk of both distributions lies below that threshold. The other salient feature of these densities is that most of the improvements for Black people relative to Whites between 2000 and 2015 come from compressing the upper portion of the pollution distribution, a point to which we will return.

¹¹ Due to census disclosure avoidance review, we were forced to trim the upper ninety-seventh and lower third percentiles of each pollution distribution.

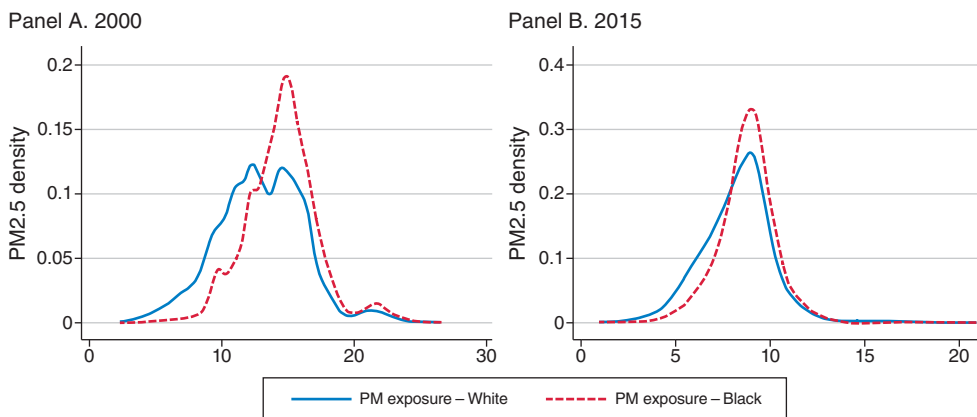


FIGURE 2. DISTRIBUTIONS OF POLLUTION EXPOSURE, 2000 AND 2015

Notes: This figure plots the PM_{2.5} density, separately for African Americans and the non-Hispanic White population in both 2000 and 2015. Due to census disclosure avoidance review, we were forced to trim the upper ninety-seventh and lower third percentiles of each density.

Sources: US Census Bureau (2010, 2015) and Di et al. (2016a,b)

II. Decomposing Differences in Pollution Exposure

What explains the observed differences in pollution exposure? Perhaps lower income individuals live in more polluted places, and differences disappear or are greatly attenuated when we condition on income. Or perhaps differences in education and/or knowledge about the potential harms of PM_{2.5} exposure lead to observed differences in pollution exposure? The census demographic data allow us to explore the cross-sectional and time-series differences in pollution exposure between racial groups. The demographic data also allow us to begin to explore the extent to which individual endowments can explain the observed differences and changes. Conditional on income differences, does the observed Black-White gap in pollution exposure remain? We focus on the following individual-level characteristics measured in the census long form and ACS surveys: race, age, gender, income, education, number of children, and home ownership. We also explore the role of neighborhood characteristics in explaining pollution disparities, using census tract characteristics constructed from the underlying microdata, including mean public assistance income, the teen pregnancy rate, average years of schooling, the population share living in single family residences, and the home ownership rate. Online Appendix Table B2 presents summary statistics of these variables, separately for non-Hispanic White and African American individuals in our sample.

A. Conditional versus Unconditional Differences in Pollution Exposure

The data show a large gap in pollution exposure in 2000, which fell considerably over the next fifteen years. As a first step toward understanding the reasons for the declining gap, we start by asking whether cross-sectional differences in exposure in any given year can be explained by differences in individual characteristics from

the census and ACS. One natural way to do this is to compare the conditional mean differences in pollution exposure between racial groups to the unconditional mean differences using the following linear regression model:

$$(1) \quad P_i = \gamma \mathbf{1}[\text{African American}]_i + X_i' \beta + \epsilon_i,$$

where pollution for individual i is regressed on an indicator for whether or not the individual is African American, controlling for individual demographic characteristics in the vector (X). Specifically, we control for individual income, age, education, number of children, gender, and an indicator for homeownership. Regressions are weighted using survey weights, and inference is conducted with cluster-robust standard errors, clustering by commuting zone (CZ). Figure 3, panel A plots the coefficient γ and associated confidence intervals from 15 separate regressions, one per year, representing the conditional mean differences in Black-White pollution exposure over time. Figure 3, panel B compares these estimates to the unconditional mean differences in pollution exposure over time. The lines look almost identical. This similarity implies that differences in individual characteristics, such as income, explain almost none of the cross-sectional differences in pollution exposure between African Americans and non-Hispanic Whites. This fact is shown more formally in online Appendix Table B3. Online Appendix Table B3 also shows that including the covariates more flexibly adds little explanatory power.¹² This conclusion is striking considering that African American households have mean household income more than \$15,000 lower than non-Hispanic Whites (see online Appendix Table B2). These differences in income and other characteristics explain almost none of the observed differences in pollution exposure. Online Appendix A.A1 formally decomposes these cross-sectional differences in mean pollution exposure using methods pioneered by Oaxaca (1973) and Blinder (1973). Observable differences in individual and household characteristics are able to explain at most 8 percent of the gap in mean differences in any given year. Of these characteristics, differences in homeownership rates tend to matter most (accounting for between 4–6 percent of the total difference). On net, African Americans are more likely to be renters, and rental housing is disproportionately exposed to PM2.5.

Gaps in pollution exposure are also found at different points within the income distribution. Table 1 presents the results from ten separate estimates of γ from equation (1), where we stratify the data by income quintiles in both 2000 and 2015. At each quintile, the conditional gap remains similar to the unconditional gap in a given year. Differences in individual characteristics do little to explain the mean differences in pollution exposure within these income categories.

Equation (1) and the Oaxaca-Blinder exercise in online Appendix A.A1 are well suited for decomposing differences in mean Black-White pollution exposure. However, Figure 2 suggests that there exist additional racial differences at different quantiles of the pollution distribution. A natural question to ask is whether differences in individual or household characteristics are able to explain differences in pollution exposure at other parts of the pollution distribution. DiNardo,

¹² We have repeated all of our analyses using this more flexible set of controls and found that the estimates were the same to the third decimal point.

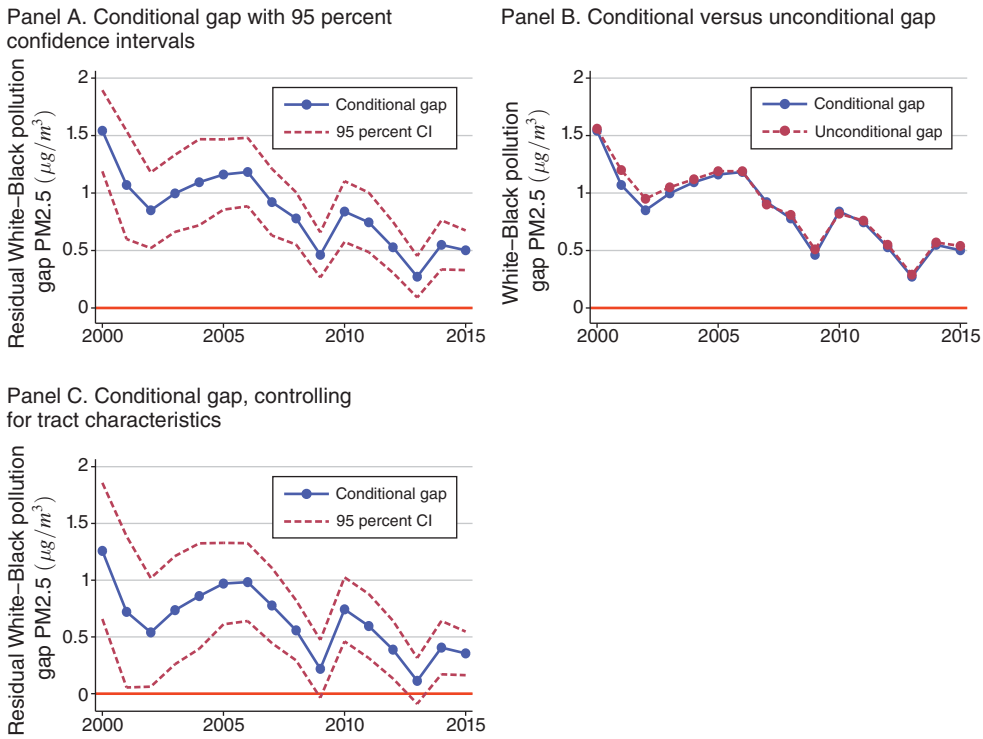


FIGURE 3. RESIDUAL BLACK-WHITE POLLUTION GAP: PM2.5

Notes: Panel A plots the regression coefficients from 15 separate estimates of equation (1), regressing pollution on an indicator for whether an individual is African American, controlling for individual and household characteristics. The coefficient estimates correspond to the conditional mean Black-White difference in air pollution, after adjusting for differences in observable individual and household characteristics. Dashed lines correspond to 95 percent confidence intervals, where standard errors have been clustered by CZ. Regressions are weighted using census survey weights. Panel B compares the conditional mean coefficients to the unconditional mean differences by year. Panel C replicates panel A while also controlling for census tract or “neighborhood” characteristics. See text for details.

Sources: US Census Bureau (2010, 2015) and Di et al. (2016a,b)

Fortin, and Lemieux (1996) provide a straightforward semiparametric approach to answering this question. The basic idea is to estimate what the entire *distribution* of African American pollution exposure would look like if African Americans had the same observable characteristics as non-Hispanic Whites. In practice, this amounts to constructing a weighting function that is then used to reweight a kernel density estimate of the African American pollution distribution to provide the relevant counterfactual distribution African Americans would have experienced given the same characteristics as non-Hispanic Whites. This weighting function boils down to estimating a conditional probability of being a non-Hispanic White individual based on observable, demographic characteristics via a probit regression. This conditional probability is then used, along with the unconditional probabilities of being White/Black in our sample to reweight the African American kernel density in a given year.

TABLE 1—RESIDUAL BLACK-WHITE POLLUTION GAP BY INCOME QUINTILE: PM2.5

	Income quintile				
	1	2	3	4	5
<i>Panel A. Year 2000</i>					
$\mathbf{1}$ [African American]	1.535 (0.180)	1.603 (0.190)	1.616 (0.193)	1.590 (0.195)	1.396 (0.183)
Observations	1,791,000	1,967,000	2,397,000	2,277,000	2,204,000
<i>Panel B. Year 2015</i>					
$\mathbf{1}$ [African American]	0.499 (0.097)	0.463 (0.093)	0.512 (0.096)	0.558 (0.089)	0.570 (0.099)
Observations	235,000	223,000	224,000	226,000	244,000

Notes: This table presents the regression coefficients from ten separate estimates of equation (1), five per panel. We regress pollution on an indicator for whether an individual is an African American, controlling for individual and household characteristics, and we stratify the data by income quintile. The coefficient estimates correspond to the conditional mean Black-White difference in air pollution, after adjusting for differences in observable individual and household characteristics. Panel A does this for the year 2000, and panel B repeats this exercise in 2015. Regressions are weighted using census survey weights, and standard errors are clustered by CZ. See text for details.

Sources: US Census Bureau (2010, 2015) and Di et al. (2016a,b)

The results from this exercise are presented in online Appendix Figure B2. Online Appendix Figure B2a presents estimates of the counterfactual pollution distribution in 2000, and online Appendix Figure B2b presents estimates of the counterfactual pollution distribution in 2015. In both cases, the counterfactual density looks very similar to the actual density, again suggesting that individual characteristics are able to explain little of the observed pollution gap throughout the distribution. Online Appendix A.A2 and online Appendix Table B5 use methods proposed by Firpo, Fortin, and Lemieux (2009) to formally decompose the tenth, fiftieth, and ninety-th percentile of the pollution distribution into the parts that can be explained by observable covariates versus the part that remains unexplained. Once again, we find that little can be explained by observable individual-level characteristics from census data.

B. Controlling for Neighborhood Characteristics

While individual and/or household characteristics explain little of the Black-White pollution gap, there is substantial racial segregation into different areas within and across communities. Are the differences in the socioeconomic characteristics of Black and White neighborhoods able to explain these gaps in exposure? Panel 2 of online Appendix Table B2 presents mean census tract characteristics, separately for non-Hispanic Whites and African Americans. African Americans not only have different individual- and household-level characteristics on average, but they also tend to be concentrated in census tracts with a higher percentage of relatively disadvantaged neighbors. Note that there is nothing mechanical about this—if neighborhoods were perfectly integrated in terms of race and socioeconomic status, then everyone would live in a similar census tract regardless of their own characteristics. Hence, we can

control for characteristics of neighborhoods or census tracts as well as characteristics of individuals in equation (1) in order to explore whether Black-White differences in neighborhood characteristics (conditional on individual characteristics) are able to explain some of the observed differences in PM2.5 exposure.

Figure 3, panel C shows the results of adding neighborhood characteristics to equation (1), and online Appendix Table B6 presents the associated Oaxaca-Blinder decomposition. Specifically, we add census-tract level measures of mean public assistance income, the teen pregnancy rate, years of schooling, the share living in single family residences, the home ownership rate, miles of major highways, and total facility PM2.5 emissions to equation (1). Figure 3, panel C, which plots year-by-year estimates of γ , looks quite similar to Figure 3, panel A. Namely, the conditional gap in pollution exposure between African Americans and non-Hispanic Whites is also not fully explained by mean differences in neighborhood characteristics. Online Appendix Table B6 explores this result in greater detail. The table shows the fraction of the gap that is “explained” and “unexplained” by each variable separately, as well as the combined effect of these neighborhood characteristics. As one can see from the “explained” panel of online Appendix Table B6, Black-White differences in neighborhood characteristics explain 0.324 of the documented 1.617 gap in PM2.5 exposure. Most notably, the tract home ownership rate explains the largest share of the difference. In both 2000 and 2015, mean differences in the tract home ownership rate explain about 20 percent of the difference in PM2.5 exposure. There are also substantial differences in the returns or responsiveness of individuals to differences in neighborhood characteristics (i.e., panel B); a one-year increase in the mean census tract education translates into substantially less pollution exposure for White people than it does for Black people in our sample, which is reflected in the relatively large difference in estimated “slopes” on the “tract years of schooling” variable in panel B.

The fact that African Americans live in different neighborhoods than non-Hispanic Whites explains some of the gap in pollution exposure but also raises further questions. Does the shrinking of the racial gap in pollution exposure come from improvements in air quality in neighborhoods that have higher shares of African Americans, or is the improvement due to the relative movement of African Americans away from dirty neighborhoods toward cleaner ones? We next present an additional decomposition which attempts to shed light on these questions.

C. People versus Places: Understanding How Relative Mobility Has Affected Pollution Disparities

One straightforward way to understand the role of mobility in contributing to the convergence in pollution exposure between Black and White Americans is to consider what the pollution gap in 2015 would have been if we fixed individuals in their 2000 locations but let pollution in their fixed census blocks change to its 2015 level. For this counterfactual exercise, we use the public-use 100 percent count population data from the 2000 decennial census at the census block level. We merge these data to the 2000 and 2015 Di et al. (2016a,b) data to calculate mean exposure gaps using block-level population counts for non-Hispanic Whites and African Americans. Table 2 presents results from this counterfactual exercise.

TABLE 2—COUNTERFACTUAL POLLUTION LEVELS AND GAPS HOLDING LOCATION FIXED

	Actual 2000 exposure (1)	Actual 2015 exposure (2)	Counterfactual 2015 using 2000 locations (3)
White PM2.5 $\mu\text{g}/\text{m}^3$	12.96	8.25	8.22
Black PM2.5 $\mu\text{g}/\text{m}^3$	14.52	8.79	8.89
Black-White difference	1.56	0.54	0.67
Change in Black-White difference		1.02	0.89

Notes: Rows 1 and 2 of columns 1 and 2 present mean pollution exposure separately for African American and non-Hispanic Whites in years 2000 and 2015. Row 3 presents the mean gap in pollution exposure in either each year. Row 4 presents the change in Black-White gap between 2000 and 2015. Column 3 presents a counterfactual exercise, whereby we ask what pollution levels would be and by how much the gap would have converged between 2000 and 2015 if we fixed the population in their 2000 location and assigned the 2015 pollution levels for their respective census block.

Sources: US Census Bureau (2010, 2015) and Di et al. (2016a,b)

Columns 1 and 2 present the actual pollution levels experienced by Black and White Americans in 2000 and 2015, and the associated gap (row 3) and change in gap (row 4). Column 3 of Table 2 shows the results of a counterfactual exercise, where we simulate what the gap (and change in gap) would have been in 2015 if people's locations had been held fixed. The last row of column 3 tells us that the change in the pollution gap would have been slightly smaller if individuals had been unable to move between 2000 and 2015. African Americans moved to relatively cleaner places between 2000 and 2015, and the opposite is true for non-Hispanic Whites.¹³ If populations were fixed in their 2000 locations, the gain would have been 0.89 $\mu\text{g}/\text{m}^3$ versus the 1.02 $\mu\text{g}/\text{m}^3$ actually experienced. Thus, only 12.7 percent of the improvement in the exposure gap stems from differences in the mobility patterns between African Americans and non-Hispanic Whites over this time period, leaving the rest to be explained by a greater improvement in pollution in predominantly African American areas.

Online Appendix A.A3 presents additional results that explore the year-by-year changes in Black-White population shares and pollution exposure in order to shed further light on the role of mobility in explaining pollution gaps. This analysis shows that the negative relationship between White population shares and pollution levels has weakened over time. Even so, the role of relative mobility differences in explaining the closure of the gap remains small (certainly less than 15 percent).

Whether and how the mobility of White and Black people is related to *changes* in air quality over this time period is a different question. Are non-Hispanic Whites moving into the cities that experienced the largest improvements in air quality? It is possible that non-Hispanic Whites moved to the cities that were cleaning up the most rapidly, but still increased their exposure to pollution. Suppose an individual moved from the relatively less polluted suburbs toward the city center in a city

¹³This pattern is consistent with recent findings in urban economics which show that, after decades of suburbanization, the urban population became whiter and more college educated in most large US cities after 2000 (Baum-Snow and Hartley 2019; Couture and Handbury 2017), and similarly, suburbs have become more diverse. The shift in White population shares toward urban centers contributes to higher levels of average pollution exposure among Whites than they would have experienced had they remained in predominantly suburban locations.

where air quality has improved. While this individual is moving to an urban center that has cleaned up, their new air quality exposure may remain above their previous exposure. We explore these issues in more detail in subsequent sections.

III. The CAA and Relative Changes in Pollution Exposure

Thus far, we have documented that (i) the Black-White gap in exposure to particulate matter has declined substantially since 2000, and (ii) neither individual characteristics nor residential mobility of individuals appears to fully explain why this gap has declined. Rather, it appears that the Black-White gap in exposure has declined primarily because African American neighborhoods had greater improvements in air quality. But why did these particular neighborhoods experience improvements in air quality? We hypothesize that a major reason for the narrowing of the Black-White gap in air quality is that changes in the enforcement of the CAA between 2000–2015 were more binding in predominantly Black neighborhoods. We formally investigate this hypothesis below.

The CAA was first implemented in 1963, but the original legislation provided limited federal oversight of state efforts and led to disappointing results. In response, Congress enacted the CAA Amendments of 1970 and established the EPA, which vastly increased federal power to address air pollution.¹⁴ The CAA initially focused on common, dangerous, air pollutants known as “criteria air pollutants.” Compliance was to be achieved through regulations governing both stationary sources (e.g., factories) and mobile sources (e.g., cars).

For stationary sources, the CAA created pollutant-specific NAAQS that specify maximum allowable concentrations of criterion air pollutants. NAAQS were initially established for sulfur dioxide, carbon monoxide, nitrogen dioxide, lead, particulates, and eventually ozone. Stationary source regulations focus primarily on areas that are out of compliance with the NAAQS. Each year in July, the EPA determines the set of counties that are in violation or “nonattainment” of a particular NAAQS standard based on air pollution monitor measurements in those or nearby counties. The consequences of being a “nonattainment” area can be severe. State governments must develop a pollutant-specific plan, known as a State Implementation Plan, describing how areas will improve air quality and come into compliance. The EPA reviews these state plans. If a state fails to act or develops an inadequate plan, the EPA can withhold federal funding for the state air pollution control program, highway construction, and the construction of sewage treatment plants. The EPA can also ban permits for construction of major new and/or modified sources of a pollutant in communities that are out of compliance with NAAQS. In addition, the EPA can impose its own federal plan if it deems a state’s plan inadequate. Thus, the CAA gives the EPA sweeping powers to take action to improve air quality, with or without state cooperation.

Since 1970, there have been two major amendments to the CAA, in 1977 and 1990, and hundreds of additional policies designed to respond to changing scientific consensus about both the harms from pollution and feasible compliance technologies.

¹⁴Currie and Walker (2019) provide a more complete overview of the CAA and associated research by economists.

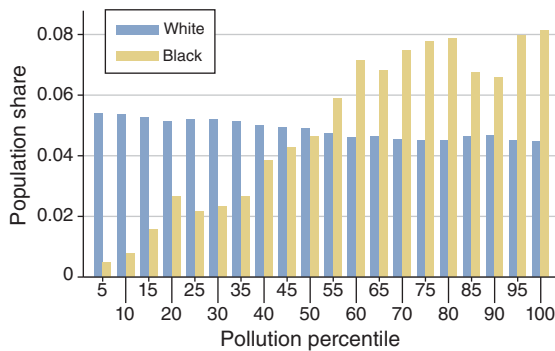
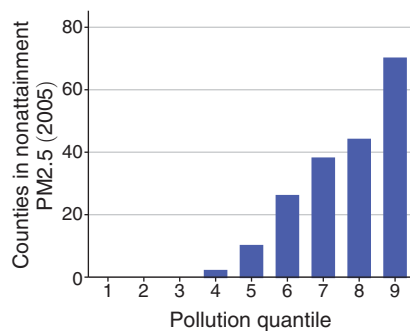
Panel A. Distribution of African American and non-Hispanic White population by decile of PM_{2.5} in 2000Panel B. Counties impacted by the CAA, by decile of PM_{2.5} in 2005

FIGURE 4. RACIAL DISTRIBUTION OF POPULATION AND IMPACT OF CAA BY POLLUTION DECILE

Notes: Panel A plots population shares by pollution decile, separately for African American and non-Hispanic Whites. Panel B shows the total number of counties subject to the CAA's 1997 NAAQS PM_{2.5} standard, by pollution decile.

Sources: US Census Bureau (2010, 2015); EPA (2022b); and Di et al. (2016a,b)

In 1997, the EPA tightened the NAAQS pertaining to ozone and particles further, regulating fine particles less than 2.5 micrometers in diameter (PM_{2.5}) for the first time. The new standards were extremely controversial and were challenged in the courts for years, but ultimately the EPA prevailed, and the new standards were implemented in April 2005. The EPA revised the PM_{2.5} (24 hour) standard again in 2006, and the revision went into effect in 2009. However, since all counties which were in nonattainment of the annual PM_{2.5} standard in 2009 were also in nonattainment of the 24 hour standard, the 2009 designations do not appear to have caused additional new areas to be subject to NAAQS nonattainment regulations. We focus on the effects of mandated reductions in annual PM_{2.5} under the 1997 standards which finally began to be implemented in 2005.

To what extent is the cleanup of predominantly African American areas a result of the implementation of these new standards? We have seen that African Americans lived in more polluted places on average in 2000, and the initial impact of the CAA was therefore likely to be greatest in these places. Figure 4, panel A shows the distribution of the African American and non-Hispanic White populations by vigintile of PM_{2.5} levels in 2000; the former were much more likely to live in the highest pollution deciles, while for Whites the situation is reversed. Figure 4, panel B shows that it was predominantly counties in the highest PM_{2.5} deciles that were impacted by the enforcement of the standards in 2005. Hence, unless the initial impact of stronger regulation was undone by re-sorting of population shares, we would expect the regulations to close gaps between Black and White Americans.

We begin by examining the effect of these new air quality standards on pollution exposure in a standard difference-in-difference, event-study design. To better mimic the way the regulations work in practice we adopt a slightly unconventional regression model when compared to the existing literature. Whenever a county exceeds the air quality standard based on a local monitoring station, the regulator decides

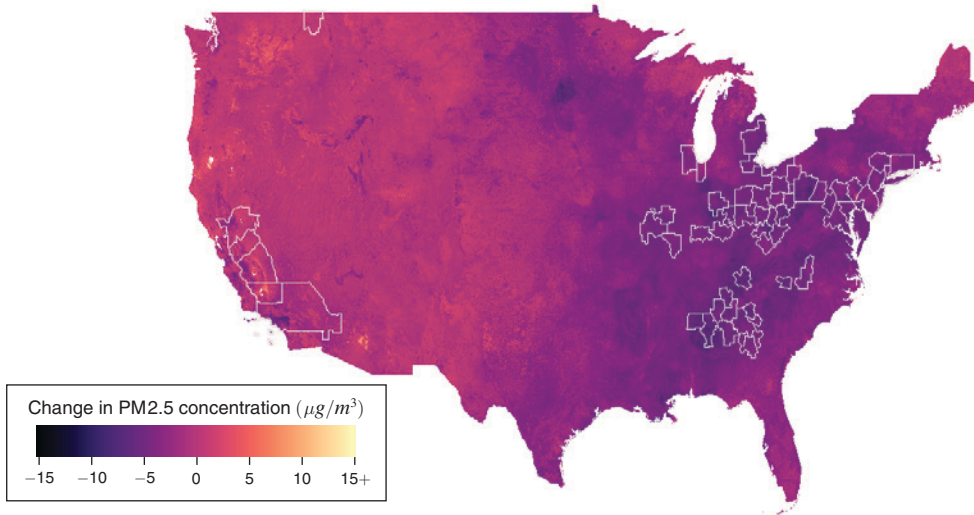


FIGURE 5. SPATIAL DISTRIBUTION OF PM_{2.5} CHANGES FROM 2000 TO 2015, OVERLAID WITH CZs IN NONATTAINMENT OF THE PM_{2.5} NAAQS

Notes: This figure plots the spatial distribution of 2000–2015 changes in PM_{2.5}. We overlay this figure with the outlines of all the CZs containing at least one nonattainment county in 2005 for the CAA’s 1997 NAAQS PM_{2.5} standard. While the PM_{2.5} NAAQS was initially proposed in 1997, the first year of regulatory enforcement began in 2005.

Sources: Di et al. (2016a,b); EPA (2022b)

whether nearby or adjacent counties could also have contributed to this violation. Thus, these nonattainment designations apply to “air regions” or groups of counties in the same local market, typically not a single county. We approximate these air region definitions using county-aggregates in the form of CZs or local labor markets.¹⁵ Figure 5 shows a map of the 2000–2015 changes in PM_{2.5}. We overlay this map with the outline of the 62 CZs, consisting of 250 counties in 20 states, that were designated as nonattainment areas in 2005. The figure illustrates that the largest reductions are concentrated the Eastern and Southeastern United States, areas with higher shares of African American residents relative to other parts of the United States that experienced less air quality improvement. The figure also suggests that the areas targeted by the new standards were among those that experienced the largest improvements in air quality.

We estimate an event study model of the following form:

$$(2) \quad P_{ict} = \sum_{t=2000}^{2015} \beta_t (\mathbf{1}[\text{Nonattain}_c] \times \mathbf{1}[\text{year}_t = t]) + \gamma_c + \rho_t + \epsilon_{ict}$$

¹⁵There is no formal EPA definition of “air regions,” as they are decided on a case-by-case basis. Thus, air regions are only defined for nonattainment areas. Our use of CZ boundaries is meant to approximate air region boundaries in the attainment areas. In practice, our results are not sensitive to using either county or CZ boundaries to assign treatment/control, but we chose the latter to better mimic the regulatory variation while also accounting for potential spatial correlation in treatment.

where pollution P_{ict} for person i residing in CZ c in year t is regressed on a series of interaction terms for whether a CZ is newly designated as nonattainment for the PM2.5 standard ($\mathbf{1}[\text{Nonattain}_c] = 1$) interacted with a dummy for each year before and after the regulations went into place. Equation (2) also controls for county fixed effects γ_c and (state-)year fixed effects ρ_t . All regressions are weighted using census survey weights, and standard errors are clustered at the CZ level.

The coefficients of interest, β_t , compare the CZs that became newly regulated under the PM2.5 standard to areas that were in compliance with the standard, before and after the regulations went into place. The identifying assumption is that the newly regulated CZs would have trended similarly, in terms of pollution levels, to the unregulated CZs in the absence of the treatment. Alternatively, the identifying assumption relies on there being no common shock to the treated CZs in the years after the regulations went into place. While these assumptions are inherently untestable, the event study design affords us a useful indirect test; we can examine the event study coefficients and trends leading up to the regulation in pollution levels between the regulated and unregulated CZs and test whether the two groups were trending similarly in the years prior to the regulation going into place.

We also estimate a version of equation (2) with an additional, three-way interaction term between indicators for ever being in nonattainment status, year, and whether the individual is African American.¹⁶ This “triple-difference” regression equation allows the impact of the CAA to vary differentially by race (i.e., do Black neighborhoods clean up more or less in newly regulated CZs when compared to White neighborhoods?).

Figure 6 presents the estimated event-study coefficients $\hat{\beta}_t$ from a version of equation (2) where the dependent variable is the pollution level for an individual survey respondent in a given year. There are two main findings. First, in the years leading up to the implementation of the regulation, the trends in air quality between the newly regulated counties and the unregulated counties are not statistically different from zero. After 2005, when the policy was first enacted, pollution levels in newly regulated counties fall by about 8 percent and remain there through the end of our sample. Online Appendix Figure B4 estimates a version of equation (2), separately for non-Hispanic Whites and African Americans. There do not seem to be significant differences in treatment effects between racial groups, but we explore this potential heterogeneity further below.

Table 3 presents the difference-in-difference analog to Figure 6 and equation (2). In particular, we replace the $\mathbf{1}[\text{year} = t]$ variable in equation (2) with a single indicator equal to one for $\text{year} \geq 2005$:

$$(3) \quad P_{ict} = \beta(\mathbf{1}[\text{Nonattain}_c] \times \mathbf{1}[\text{year}_t \geq 2005]) + \gamma_c + \rho_t + X'\eta + \epsilon_{ict}$$

¹⁶Formally, we estimate the following equation:

$$P_{ict} = \sum_{t=2000}^{2015} \beta_t(\mathbf{1}[\text{Nonattain}_c] \times \mathbf{1}[\text{year}_t = t] \times \mathbf{1}[\text{African American}_i]) + \Gamma_{ict} + \gamma_c + \rho_t + X'\eta + \epsilon_{ict}$$

where the vector Γ_{ict} includes the full set of two-way interaction terms to facilitate interpretation.

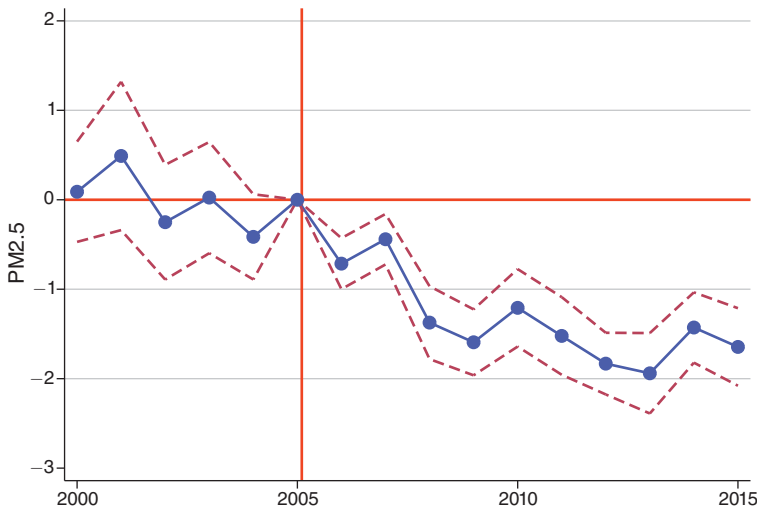


FIGURE 6. THE EFFECT OF THE PM_{2.5} NAAQS ON NEWLY REGULATED CZs

Notes: This figure plots the event-time coefficient estimates from a version of equation (2), where the dependent variable consists of PM_{2.5} exposure ($\mu\text{g}/\text{m}^3$) for a given individual-year. The regression model controls for county and year fixed effects. The dashed lines represent 95 percent confidence intervals. Regressions are weighted by census survey weights and errors are clustered by CZ.

Sources: US Census Bureau (2010, 2015); EPA (2022b); Di et al. (2016a,b)

TABLE 3—THE IMPACT OF THE 2005 IMPLEMENTATION OF PM_{2.5} STANDARDS ON PM_{2.5} LEVELS

	PM _{2.5} (1)	PM _{2.5} (2)	ln(PM _{2.5}) (3)	ln(PM _{2.5}) (4)	PM _{2.5} (5)	PM _{2.5} (6)	ln(PM _{2.5}) (7)	ln(PM _{2.5}) (8)
PM _{2.5} nonattain × post	-1.230 (0.335)	-1.237 (0.334)	-0.075 (0.020)	-0.076 (0.020)	-0.727 (0.080)	-0.726 (0.082)	-0.036 (0.006)	-0.036 (0.006)
PM _{2.5} non × black × post		0.149 (0.088)		0.008 (0.007)		0.048 (0.091)		0.004 (0.005)
Year FE	X	X	X	X				
State-Year FE					X	X	X	X
County FE	X	X	X	X	X	X	X	X
Observations	32,360,000	32,360,000	32,360,000	32,360,000	32,360,000	32,360,000	32,360,000	32,360,000

Notes: This table presents regression coefficients from 8 separate versions of equation (3), one per column, where the dependent variable consists of PM_{2.5} or ln(PM_{2.5}) for an individual in a given year. Columns 2, 4, 6, and 8 add an additional interaction for African Americans to test for heterogeneity in regulatory impacts for African Americans. Regressions are weighted by census survey weights and errors are clustered by CZ. FE = fixed effects.

Sources: US Census Bureau (2010, 2015); EPA (2022b); Di et al. (2016a,b)

The regression coefficient of interest β from this more parsimonious model tells us the average difference in pollution levels in the years after, relative to before, comparing regulated counties to counties not subject to the regulation. Column 1 suggests that PM_{2.5} levels fell by $1.23 \mu\text{g}/\text{m}^3$ in nonattainment counties in the years after the regulation went into place. Column 3 presents the same model except the

dependent variable has been transformed via the natural log. As suggested by the figures, these estimates suggest that pollution levels in newly regulated counties improved by about 8 percent in the years after the policy went into place.

The even columns of Table 3 add a triple interaction between the county ever being in nonattainment status, a post-2005 time period, and an indicator for whether the individual is African American. Recall that African Americans and non-Hispanic Whites tend to live in different parts of the same counties, so there is scope for regulation at the county-level to have a differential impact on different communities within a county. These estimates suggest that the within-county improvements in air quality were slightly less for African Americans than for non-Hispanic Whites, though the differences are not statistically significant in any specification.

Columns 5 through 8 of Table 3 add state-by-year fixed effects to equation (3) to control for any unobserved, statewide changes to air quality that are common to all individuals in a given state-year. These controls substantially attenuate the coefficients from columns 1 through 4 by almost 50 percent. There are potentially many reasons for this attenuation, having to do with unobserved, time-varying correlated unobservables. From this point forward, we treat the estimates with state-by-year fixed effects as our preferred specification in order to flexibly control for this potential form of omitted variable bias.

Online Appendix Table B8 presents a range of alternative estimates to those presented in Table 3. Columns 1 and 2 of online Appendix Table B8 replicate the baseline estimates in Table 3. Columns 3 and 4 replicate our analysis using PM2.5 exposure estimates from the EPA's existing monitoring network, instead of our satellite/remote-sensing PM2.5 estimates from Di et al. (2016a,b). Columns 5 and 6 explore estimates that forgo the use of census survey weights. Lastly, columns 7 and 8 explore the role of spatial spillovers in leading to bias in our existing estimates. Specifically, we show estimates from models that exclude any adjacent/neighboring CZs that border a treated CZ in our analysis. These estimates are a little larger than the baseline results in Table 3, indicating that our main specification is conservative.

As Figure 2 shows, there have been large improvements over time in air quality for both African Americans and non-Hispanic Whites, much larger than the treatment effects seen in Table 3. Partly this reflects differences in conditional versus unconditional changes; Table 3 includes either year or state \times year fixed effects, which net out a lot of nationwide or regional improvements in air quality. In addition, these treatment effect estimates reflect a specific aspect of the CAA's air quality regulations and apply primarily to stationary sources like factories. Mobile-source regulations, such as tailpipe emissions, are national in scope and have also led to significant national improvements in air quality over this time period.

While the estimates from Figure 6 and Table 3 tell us about the average effects in the treated counties, relative to the controls, they tell us little about other parts of the pollution distribution that might otherwise be affected by this increased regulatory stringency. To explore the distributional impacts of the PM2.5 NAAQS we turn to unconditional quantile regression estimates. We then combine our difference-in-difference estimator with quantile regression methods to estimate the counterfactual outcome distribution in the absence of the policy intervention. We compare this no-regulation, counterfactual distribution to the actual outcome

distribution when subject to the policy intervention. We then go further and calculate the mean Black-White gap in pollution exposure in this counterfactual world, to better understand the role of the CAA in contributing to the convergence of Black-White pollution levels.

Recent advances in quantile regression allow us to estimate the causal effect of the CAA's PM_{2.5} NAAQS on the unconditional pollution distribution (Firpo, Fortin, and Lemieux 2009). The basic idea is to transform the problem by considering a covariate's influence on population shares rather than quantiles. By estimating how a covariate (e.g., nonattainment status) affects the share of the population below various pollution thresholds, the semielasticities show the effect of an increase in CAA regulatory stringency on the cumulative distribution function (CDF) of pollution (see e.g., Chernozhukov et al. 2013). We can then invert the impact of nonattainment on the CDF of pollution to estimate the impact on a pollution quantile. The recentered influence function (RIF) regression approach proposed by Firpo, Fortin, and Lemieux (2009) performs this inversion using a local linear approximation to the counterfactual CDF, rescaling the marginal effect of the CAA on the population share above a pollution cutoff by the probability density of pollution at that cutoff.

The relevant property of a recentered influence function is that its expectation equals the distributional statistic of interest. Since the mean of the RIF is equal to the quantile, we can use the law of iterated expectations to go between conditional and unconditional partial effects. Firpo, Fortin, and Lemieux (2009) show that a regression of the RIF on covariates yields the approximate effect of the covariates on the distributional statistic of interest (applied to the unconditional distribution). This feature of RIF regressions allows researchers to estimate how treatment effects (e.g., the effects of the CAA PM_{2.5} regulations on county-year pollution levels) map into the unconditional distribution of pollution. Online Appendix A.A2 provides a more formal discussion.

In practice, this exercise entails first defining a series of pollution cutoffs corresponding to specified quantiles of the empirical pollution distribution, and then for each cutoff, estimating the effect of the CAA's PM_{2.5} NAAQS policy on the probability of being above that cutoff. We begin by creating 19 RIF statistics, one for each pollution vigintile from the fifth to the ninetieth percentiles of the pollution distribution. We then replace the dependent variable in equation (2) with one of the RIF-quantile statistics. The event study coefficients for each RIF-quantile can be interpreted as the effect of the PM_{2.5} nonattainment designations on the *q*th quantile of the unconditional PM_{2.5} exposure distribution.

Figure 7 presents 19 separate regression estimates of β from equation (3), where the dependent variable is replaced with the RIF counterpart for each pollution quantile.¹⁷ The figure visually summarizes the effect of the PM_{2.5} nonattainment designation on different quantiles of the unconditional PM_{2.5} pollution distribution. The estimates suggest that the most significant effects of the new standards were to improve air quality in areas between the fiftieth and ninetieth percentiles of the PM_{2.5} distribution. This result must be true almost by construction, as the PM_{2.5} standards only bind at the upper quantiles of the pollution distribution. It may be

¹⁷These regressions use population weighted percentiles of pollution exposure. This is also done in Figure 8.

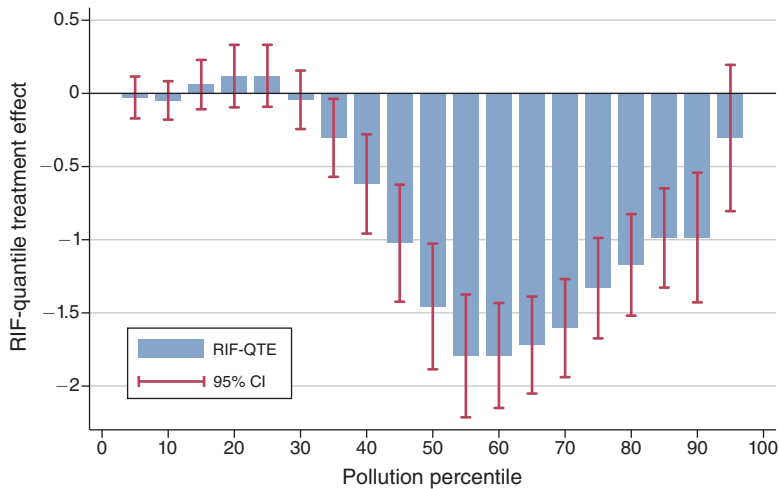


FIGURE 7. RIF-QUANTILE TREATMENT EFFECTS OF THE 2005 CAA PM_{2.5} NAAQS IMPLEMENTATION

Notes: This figure plots the regression coefficient $\hat{\beta}$ from 19 separate versions of equation (3), where the dependent variable consists of the RIF-quantile transformation of the respective PM_{2.5} vigintile (indicated by the *x*-axis). The regression model controls for county fixed effects and state-by-year fixed effects. The solid red lines represent 95 percent confidence intervals. Regressions are weighted by census survey weights and errors are clustered by CZ.

Sources: US Census Bureau (2010, 2015); EPA (2022b); Di et al. (2016a,b)

surprising to see that the estimated effect of the regulations is smaller at the ninetieth percentile of the pollution distribution than at the fiftieth to eightieth percentiles. This smaller effect may be partly due to the severe difficulties EPA and local regulators may have faced in addressing air quality problems in the most severely polluted parts of the country (e.g., the San Joaquin Valley or parts of Southern California). Online Appendix Figure B5 presents the event study specification of these regressions to better understand both the temporal dynamics of these treatment effects and also to assess common trends, when using different transformations of individual PM_{2.5} exposure.

Figure 8 presents RIF-quantile regression results that estimate each quantile specific RIF separately by race. This results in 38 versions of equation (3), and the corresponding estimates are plotted in Figure 8. While the estimates from Table 3 suggested there was little difference in the treatment effects of nonattainment between African Americans and non-Hispanic Whites on average (see e.g., column 6), the results in Figure 8 suggest that at the upper quantiles of the pollution distribution, African Americans have seen larger improvements in air quality relative to their non-Hispanic White counterparts. For visual clarity, we have omitted the associated confidence intervals, but they are shown in online Appendix Figure B6. For most quantiles, the race-specific confidence intervals overlap with one another, and thus it is difficult to reject the null that the treatment effects at each quantile are equal. That being said, it is unlikely that sampling variability alone could explain the fact that African Americans have larger treatment effects at every percentile above the sixtieth percentile of the pollution distribution.

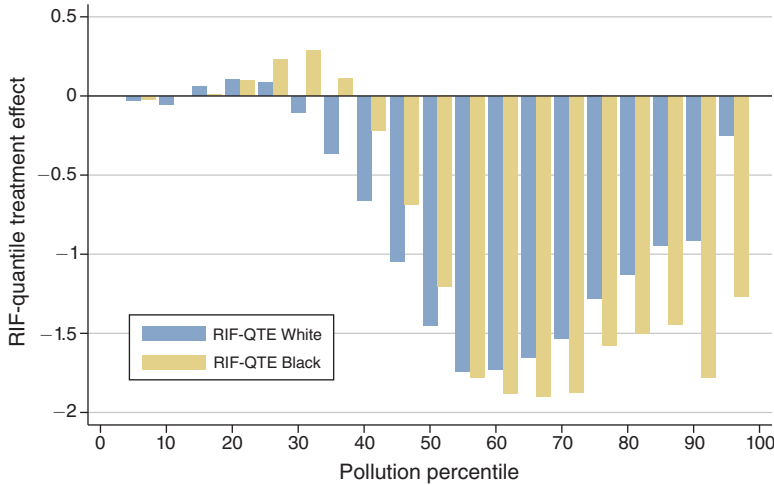


FIGURE 8. RACE-SPECIFIC RIF-QUANTILE TREATMENT EFFECTS OF THE 2005 CAA PM_{2.5} NAAQS IMPLEMENTATION

Notes: This figure plots the regression coefficient $\hat{\beta}$ from 38 separate versions of equation (3), 19 regressions for each race, where the dependent variable consists of the RIF-quantile transformation of the respective PM_{2.5} vignette (indicated by the x -axis). The regression model controls for county fixed effects and state-by-year fixed effects. Regressions are weighted by census survey weights and errors are clustered by CZ.

Sources: US Census Bureau (2010, 2015); EPA (2022b); Di et al. (2016a,b)

A. What Fraction of Black-White Convergence Is Attributable to the CAA Regulation of PM_{2.5}?

We can use the RIF estimates from Figure 8, combined with population shares of African Americans and non-Hispanic Whites in each vignette of the initial distribution of PM_{2.5}, to compute counterfactual pollution levels in the absence of the implementation of the nonattainment designations. For the calculations in this exercise, we use tract-level population shares by race from the public-use ACS five-year files. Table 4 walks through these calculations. Columns 1 and 2 of the top panel describe actual pollution levels within each quantile bin in 2005 and 2015, respectively. Columns 3 and 4 use estimates from Figure 8 to calculate what pollution in each quantile would have been in 2015 in the absence of the CAA PM_{2.5} NAAQS implementation, separately for African Americans and non-Hispanic Whites.

The second panel of Table 4 considers the counterfactual gap that would have existed in 2015 in the absence of the CAA PM_{2.5} NAAQS. The actual gap in 2015 was $0.61 \mu\text{g}/\text{m}^3$, whereas the counterfactual gap is $0.97 \mu\text{g}/\text{m}^3$. The actual *change* in the Black-White gap between 2005 and 2015 was $0.59 \mu\text{g}/\text{m}^3$, and the implied counterfactual change is a narrowing of $0.23 \mu\text{g}/\text{m}^3$. Since, we would have observed a $0.23 \mu\text{g}/\text{m}^3$ improvement in the Black-White gap in the absence of the policy, we conclude that the CAA can account for over 60 percent of the relative improvement in Black-White outcomes.¹⁸

¹⁸This is calculated as $(0.59 - 0.23)/0.59$. Note, that we can do the same counterfactual using the average population estimates from Table 3, weighting groups appropriately. The virtue of using the RIF estimates stems from a

TABLE 4—CALCULATING THE EFFECT OF CAA REGULATIONS ON THE BLACK-WHITE PM_{2.5} GAP

PM _{2.5} quantile bin (1)	Actual PM _{2.5} in 2005 (2)	Actual PM _{2.5} in 2015 (3)	White counterfactual PM _{2.5} in 2015 without CAA (4)	Black counterfactual PM _{2.5} in 2015 without CAA (5)
5	5.32	4.34	4.37	4.36
10	7.87	5.63	5.69	5.63
15	8.91	6.25	6.18	6.24
20	9.65	6.72	6.62	6.62
25	10.33	7.11	7.03	6.88
30	10.90	7.45	7.56	7.17
35	11.42	7.75	8.12	7.64
40	11.90	8.01	8.67	8.23
45	12.34	8.24	9.28	8.92
50	12.73	8.44	9.89	9.65
55	13.09	8.65	10.39	10.43
60	13.44	8.84	10.57	10.73
65	13.80	9.03	10.68	10.93
70	14.15	9.22	10.75	11.09
75	14.51	9.42	10.71	11.00
80	14.91	9.67	10.80	11.17
85	15.27	9.98	10.93	11.43
90	15.72	10.49	11.41	12.27
95	17.01	12.21	12.46	13.48

Main counterfactual: including 2005–2015 mobility responses

2005 actual Black-White gap:	1.20
2015 counterfactual Black-White gap:	0.97
Counterfactual change in Black-White gap:	−0.23
Actual change in Black-White gap:	−0.59
Percent of actual gap attributable to CAA:	61.20

Notes: This table presents calculations used to explore what fraction of the observed racial convergence in mean PM_{2.5} levels can be attributed to the regulatory variation embedded into the CAA's 2005 PM_{2.5} NAAQS. The top panel describes actual pollution levels within each quantile bin in 2000 and 2015. Columns 4 and 5 use estimates from Figure 10 to calculate what pollution would be in 2015 in the absence of the CAA PM_{2.5} NAAQS implementation, separately for African Americans and non-Hispanic Whites. The second panel computes the counterfactual gap in 2015 in the absence of the CAA NAAQS and the implied 2005–2015 change in the gap.

Sources: US Census Bureau (2010, 2015); EPA (2022b); Di et al. (2016a,b)

B. Mobility Responses to CAA-Induced Improvements in PM_{2.5} Air Quality

Previous sections suggest that relative mobility plays a limited role in explaining the convergence in PM_{2.5} exposure between African Americans and non-Hispanic Whites. However, it still may be the case, that populations shifted in response to the CAA-induced changes in air quality and that this may have implications for the Black-White gap in PM_{2.5} exposure. For example, it could be the case that the cities that cleaned up the most due to the CAA saw relatively larger increases in White population shares in subsequent years, unraveling some of the relative gains between racial groups had population shares remained constant.

more transparent analysis as to how the treatment effect heterogeneity disproportionately impacts places with high African American population shares.

Online Appendix Figure B7 explores this mobility response in more detail. Online Appendix Figure B7(a) plots the change in the Black population share between 2005 and 2015, separately by pollution quantile; negative numbers imply a reduction in the Black share in the particular quantile bin over this time period. These changes in population are plotted against the RIF-quantile treatment effects for Blacks in the respective quantile (i.e., taken from Figure 8). We include a linear fit that suggests the areas that saw the largest treatment effects from the CAA's nonattainment designation are also the areas where the share of African Americans declined the most. Online Appendix Figure B7(b) shows the opposite is true for non-Hispanic Whites. The quantiles which saw the largest improvements in air quality for non-Hispanic Whites saw the largest increases in White population shares over this time period. These relative shifts in mobility served to offset some of the CAA-induced convergence over this time period.

How does one reconcile the results in online Appendix Figure B7 with the earlier mobility results from Table 2 that suggested Whites have moved to relatively more polluted areas in 2015 versus where they were in 2000? These findings are not necessarily inconsistent with one another. While Whites were moving to urban areas which tended to be more polluted than the suburban areas they were leaving (i.e., Table 2), they also tended to move to the urban areas that had experienced the largest *improvements* in air quality between 2000 and 2015 (i.e., online Appendix Figure B7). Said differently, the CAA improved air quality in cities that had relatively higher Black population shares, but as those cities became cleaner they also became more White.

Thus, while mobility seems to play a limited role in explaining the *national* convergence in exposure gaps between racial groups, there is some evidence that non-Hispanic Whites are moving to the set of urban areas that have experienced the largest improvements in air quality over this time period. These areas had relatively high Black population shares before the improvements, and thus differential mobility has offset some of the relative gains in pollution exposure between these groups.

IV. Conclusion

This paper shows that racial differences in ambient particulate exposure declined significantly between 2000 and 2015. We add to the small but growing literature using high-resolution, nationwide data on pollution to examine racial differences in potential pollution exposure. We focus on PM_{2.5} and show that the gap between African Americans and non-Hispanic Whites narrowed from $-1.6 \mu\text{g}/\text{m}^3$ in 2000 to $-0.5 \mu\text{g}/\text{m}^3$ by 2015. To our knowledge, this is the first paper to explore the underlying causal drivers that contributed to the narrowing of this gap. We find that very little of the decline in the gap in mean exposure levels can be accounted for by changes in mobility, individual-, or neighborhood-level characteristics. Similarly, we find that racial gaps in exposure have narrowed at each quantile of the PM_{2.5} distribution, and that little of this narrowing can be explained by the demographic characteristics available in census data. Instead, we find that virtually all of the closure of the gap is due to falling pollution levels in the areas where African Americans are more likely to live. There is little evidence that movement of African Americans

to relatively cleaner neighborhoods or non-Hispanic Whites to relatively dirtier neighborhoods has played a significant role in the observed convergence.

Why then has pollution fallen more in areas that are home to greater numbers of African Americans? Since African Americans have historically been concentrated in areas with more polluted air, and because the CAA targets the dirtiest areas for cleanup, it is reasonable to expect that the CAA could have a larger impact on African Americans. However, set against this expectation are market forces that might cause African Americans in search of lower rents to move away from newly cleaner places. Our analysis shows that implementation of new PM2.5 standards in 2005 sharply reduced pollution in a way that was sustained over time and is responsible for much of the closure of the racial gap in PM2.5 exposure between 2000 and 2015. We find some evidence, however, to suggest that changes in PM2.5 levels were associated with resorting of African Americans across areas in ways that undid some of these gains.

These findings suggest that the CAA has likely played a significant role in reducing racial gaps in exposure to air pollution, because the legislation systematically targeted the dirtiest areas for cleanup, and African Americans were more likely to live in areas with dirty air. Hence, although it was not their primary intent, the CAA has contributed to reductions in environmental inequality between racial groups in the United States.

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