Disparities in Distribution of Particulate Matter Emissions from US Coal-Fired Power Plants by Race and Poverty Status After Accounting for Reductions in Operations Between 2015 and 2017

Jennifer Richmond-Bryant, PhD, Ihab Mikati, BS, Adam F. Benson, MPH, Thomas J. Luben, PhD, and Jason D. Sacks, MPH

Objectives. To investigate potential changes in burdens from coal-fired electricity-generating units (EGU_{cf}s) that emit fine particulate matter ($PM_{2.5}$, defined as matter with a nominal mean aerodynamic diameter of ≤ 2.5 μm) among racial/ethnic and economic groups after reduction of operations in 92 US EGU_{cf}s.

Methods. $PM_{2.5}$ burdens calculated for EGUs listed in the 2008, 2011, and 2014 National Emissions Inventory were recalculated for 2017 after omitting emissions from 92 EGU_{cf}s. The combined influence of race/ethnicity and poverty on burden estimates was characterized.

Results. Omission of 92 EGU_{cf}s decreased $PM_{2.5}$ burdens attributable to EGUs by 8.6% for the entire population and to varying degrees for every population subgroup. Although the burden decreased across all subgroups, the decline was not equitable. After omission of the 92 EGU_{cf}s, burdens were highest for the below-poverty and non-White subgroups. Proportional disparities between White and non-White subgroups increased. In our combined analysis, the burden was highest for the non-White–high-poverty subgroup.

Conclusions. Our results indicate that subgroups living in poverty experience the greatest absolute burdens from EGU_{cf}s. Changes as a result of EGU_{cf} closures suggest a shift in burden from White to non-White subgroups. Policymakers could use burden analyses to jointly promote equity and reduce emissions. (*Am J Public Health*. 2020;110:655–661. doi:10.2105/AJPH.2019.305558)

Marginalized communities may be at increased risk for exposure to and health effects of particulate matter with a nominal mean aerodynamic diameter of less than or equal to 2.5 micrometers ($PM_{2.5}$) emitted by industrial facilities. Communities of color and communities affected by poverty are more likely to live near significant sources of air pollution (e.g., industrial facilities)[1] or in locations with elevated ambient concentrations[2,3] than are communities made up mostly of non-Hispanic people of White race (hereafter White). Recently, Mikati et al.[4] found that the burden from all $PM_{2.5}$–emitting facilities in close proximity to an individual's census block group centroid was 89% higher among non-Hispanic people of Black race (hereafter Black) than among White people. Similarly, the burden among those below the poverty line was 47% higher than among those above the poverty line. The public health ramifications of $PM_{2.5}$ exposure have been demonstrated in several large-scale epidemiological studies reporting relationships between both short- and long-term $PM_{2.5}$ exposures and mortality.[5–11] Moreover, several studies have shown higher-magnitude health effect associations for Black and Hispanic populations than for White populations[12–15] and, in some cases, for populations below the poverty line.[14,15]

Although air pollution reduction strategies are designed to provide broad public health benefits, these benefits are not always distributed equitably. Gelobter[16] examined reductions in total suspended particulate concentrations that were attributable to the National Ambient Air Quality Standards and stratified results from 1970 to 1984 by race and income. He found that the largest reductions consistently occurred among the highest income group and those who were White. However, this analysis was limited to urban areas as a means of controlling for confounding between race and urbanicity. More recently, Nguyen and Marshall[17] observed that reductions in diesel particulate matter sources designed to decrease disparities in exposures across the population did not decrease inequities in all locations, where inequity of exposures was defined to mean the average exposure among subgroups (e.g., race/ethnicity or poverty/nonpoverty) would not be the same.

Coal-fired power plant emissions represent direct $PM_{2.5}$ sources that present risks to surrounding communities in terms of both exposure to and potential health

ABOUT THE AUTHORS

At the start of the study, Jennifer Richmond-Bryant, Thomas J. Luben, and Jason D. Sacks were with the National Center for Environmental Assessment, Office of Research and Development, US Environmental Protection Agency, Research Triangle Park, NC. Ihab Mikati and Adam F. Benson were with the Oak Ridge Institute for Science and Education, Research Triangle Park, NC. Jennifer Richmond-Bryant is with the Department of Forestry and Environmental Resources and the Center for Geospatial Analytics, North Carolina State University, Raleigh. Ihab Mikati is with New York University School of Law, New York, NY. Adam F. Benson is with The Schroeder Institute at the TRUTH Initiative, Washington, DC.

Correspondence should be sent to Jason Sacks, MPH, Center for Public Health and Environmental Assessment, Office of Research and Development, US Environmental Protection Agency, 109 TW Alexander Drive, Research Triangle Park, NC 27711 (e-mail: sacks.jason@epa.gov). Reprints can be ordered at http://www.ajph.org by clicking the "Reprints" link.

This article was accepted December 28, 2019.

doi: 10.2105/AJPH.2019.305558

effects from $PM_{2.5}$.[18] Henneman et al.[19] combined National Emissions Inventory (NEI) data for $PM_{2.5}$ from coal-fired electricity-generating units (EGU_{cf}s) with the Hybrid Single Particle Lagrangian Integrated Trajectory dispersion model and the Community Multiscale Air Quality Model to predict population-weighted $PM_{2.5}$ exposures. $PM_{2.5}$ exposures were predicted to be highest in the Ohio Valley region, and the largest decreases between 2005 and 2012 in $PM_{2.5}$ exposures overall and exposures due to coal-fired power plants were also found to occur in that region.[19] In 2014, roughly 13 000 deaths were reported to be attributable to $PM_{2.5}$ emitted by EGU_{cf}s.[18] Monetary costs of deaths in the United States attributable to $PM_{2.5}$ from coal-fired power plants range from \$30 000 to \$150 000 per ton of $PM_{2.5}$ emitted.[20–22]

The costs and benefits of electricity generated by EGU_{cf}s have been shown to be inequitably distributed. Tessum et al.[18] calculated an inequity index to compare source-specific $PM_{2.5}$ exposure with $PM_{2.5}$ attributed to consumption patterns among Black, Hispanic, and White subgroups in the United States. Their results indicated inequities among the Black subgroup, which was exposed to 43% more $PM_{2.5}$ from EGU_{cf}s than produced via electricity consumption. The Hispanic and White subgroups, respectively, were exposed to 12% and 9% less $PM_{2.5}$ from EGU_{cf}s than produced via electricity consumption.

Since 2014, 92 US EGU_{cf} facilities have retired operations of at least 1 unit.[23–25] The objective of this follow-up to Mikati et al.[4] was to investigate how the burden from $PM_{2.5}$-emitting EGU_{cf}s has potentially changed among racial/ethnic and poverty/nonpoverty subgroups after EGU_{cf} closures. We calculated burdens as a result of fossil fuel combustion according to race/ethnicity and poverty status for 2008, 2011, and 2014 and estimated the burden for 2017 by omitting coal-fired power plants with retired operations from our analyses. We compared the 2017 burden with the burdens calculated by randomly classifying coal-fired power plants as closed to assess whether actual closures may have been selected in a nonrandom fashion. Finally, we examined trends in burdens due to fossil fuel combustion according to the combined influence of race/ethnicity and poverty status.

METHODS

The concept of "burden" regarding emissions combines residential proximity to emitting facilities with the magnitude of emissions. This analysis extended the work of Mikati et al.[4] by calculating the burden of $PM_{2.5}$ emitted from EGU_{cf}s on race/ethnicity and poverty/nonpoverty subgroups and then investigating how the burden has changed as a result of facilities retiring some or all of their operations. The NEI does not report unit-specific emissions within a facility, so it was not possible to omit from our analyses only those emissions attributable to a single unit's closure within a larger facility. Therefore, we assumed that the entire facility was retired, knowing that burdens may have been underestimated at locations where only one unit was retired. Nationwide burdens were recomputed after removal of retired facilities and compared with burdens calculated for 2014 prior to facility closures.

Data Sources

We accessed self-reported 2012 to 2016 population data from the American Community Survey (ACS) at the census block group level.[26] Designated ACS race/ethnicity subgroups included White and non-White, which included all other races/ethnicities, Hispanic persons, and Black persons. Similarly, designated income subgroups included those at or below the poverty line and those above the poverty line. These subgroups were compared with the total population.

The NEI database contains data for point, nonpoint, on-road, nonroad, and event sources submitted to the US Environmental Protection Agency by local, state, and tribal governments.[27] We selected stationary anthropogenic point source data for primary $PM_{2.5}$ emissions (tons per year) from each fossil-fuel EGU reported to the NEI in 2008, 2011, and 2014 using the North American Industry Classification System code for all fossil fuels; a separate code specific to EGU_{cf}s was not available. Ninety-two EGU_{cf}s with retired coal-fired operations during 2015, 2016, and 2017 were identified in 32 states across the nation by using data from the US Energy Information Administration.[23–25] Within these 92 facilities, 191 units were permanently shut down.

NEI $PM_{2.5}$ emissions data for each source in 2008, 2011, and 2014 were merged with demographic data from the 2012 to 2016 version of the ACS at the census block group level into a single data set as follows.[26] The location of each facility within the NEI was given by latitude and longitude.[27] A facility was then assigned to block groups via the "centroid containment" assignment method described by Mikati et al.[4] and originally presented by Boyce and Pastor,[28] in which a facility is assigned to any block groups for which its centroid falls within 2.5 miles. Mikati et al.[4] performed sensitivity testing of the radius used for these calculations and determined little difference when radii between 0.5 and 5.0 miles were tested. The population counts for each subgroup were assigned to each facility when a block group was mapped to a facility.

Data Analysis

Burdens were calculated for each census block group and then aggregated to the national scale following the procedure detailed in Mikati et al.[4] Absolute burden (AB in Equation 1) was defined as the population-weighted average emissions in a block group:

$$AB = \frac{\sum (Population_{BG} \times Emissions_{BG})}{\sum Population_{BG}} \quad (1)$$

Absolute burden can be calculated for the entire population or for a specific subgroup (e.g., Black or above the poverty line). Proportional burden (PB in Equation 2) was defined as the ratio of absolute burden among one subgroup to absolute burden among the total population:

$$PB_{subgroup} = \frac{AB_{subgroup}}{AB_{total}} \quad (2)$$

A proportional burden greater than 1.0 signified that the subgroup had a higher absolute burden than the total population. A score of 1.0 in every subgroup would indicate an equitable distribution of emissions.

Initially, 2008, 2011, and 2014 NEI data were used to calculate $PM_{2.5}$ absolute and proportional burdens attributable to EGU_{cf}s for each subgroup. Next, to obtain the 2017 burden due to $PM_{2.5}$ emissions from EGU_{cf}s, we omitted EGU_{cf}s that retired operations between 2015 and 2017[23–25] from units listed in the 2014 NEI when computing burdens as a result of $PM_{2.5}$ emissions. We estimated 2017 absolute and proportional burdens by omitting $PM_{2.5}$ emissions associated with the 92 facilities where at least 1 unit had ceased operations from our analysis of 2014 NEI data.

We conducted a sensitivity analysis in which we compared burdens computed after omitting the EGU_{cf}s that were retired with burdens computed after removing EGU_{cf}s at random for each subgroup. Large differences between the burdens computed from actual facility closures and from random closures would indicate inequitable burdens across the population. We conducted a Monte Carlo analysis to assess whether burdens calculated after omission of retired EGU_{cf}s differed from burdens calculated after omission of 92 facilities at random from the 1881 NEI fossil fuel combustion facilities. The simulations were repeated 1000 times. Absolute and proportional burden means and 95% confidence intervals (CIs) from Monte Carlo analyses were plotted alongside those from the full 2014 NEI and reduced EGU_{cf} analyses.

We explored the combined influence of race/ethnicity and poverty status by computing burdens for each subgroup before and after the EGU_{cf}s were retired and comparing the results for each subgroup with those for the total population. It was not possible to identify the numbers of ACS participants fitting into different permutations of race/ethnicity–poverty groupings at the block group level.[26] For this reason, we developed the following joint subgroupings:

- Non-White–poverty stratum: block groups that are nationally in the top quartile with respect to both non-White population and individuals living below the poverty line
- Non-White–nonpoverty stratum: block groups that are nationally in the top quartile with respect to both non-White population and individuals living above the poverty line
- White–poverty stratum: block groups that are nationally in the top quartile with respect to both White population and individuals living below the poverty line
- White–nonpoverty stratum: block groups that are nationally in the top quartile with respect to both White population and individuals living above the poverty line

Absolute burdens were computed for each of the block groups fitting the previously mentioned criteria, and these burdens were compared with those calculated from the ACS population.[26] We used R version 3.1.2 (R Foundation for Statistical Computing, Vienna, Austria) in managing data and conducting our analyses.

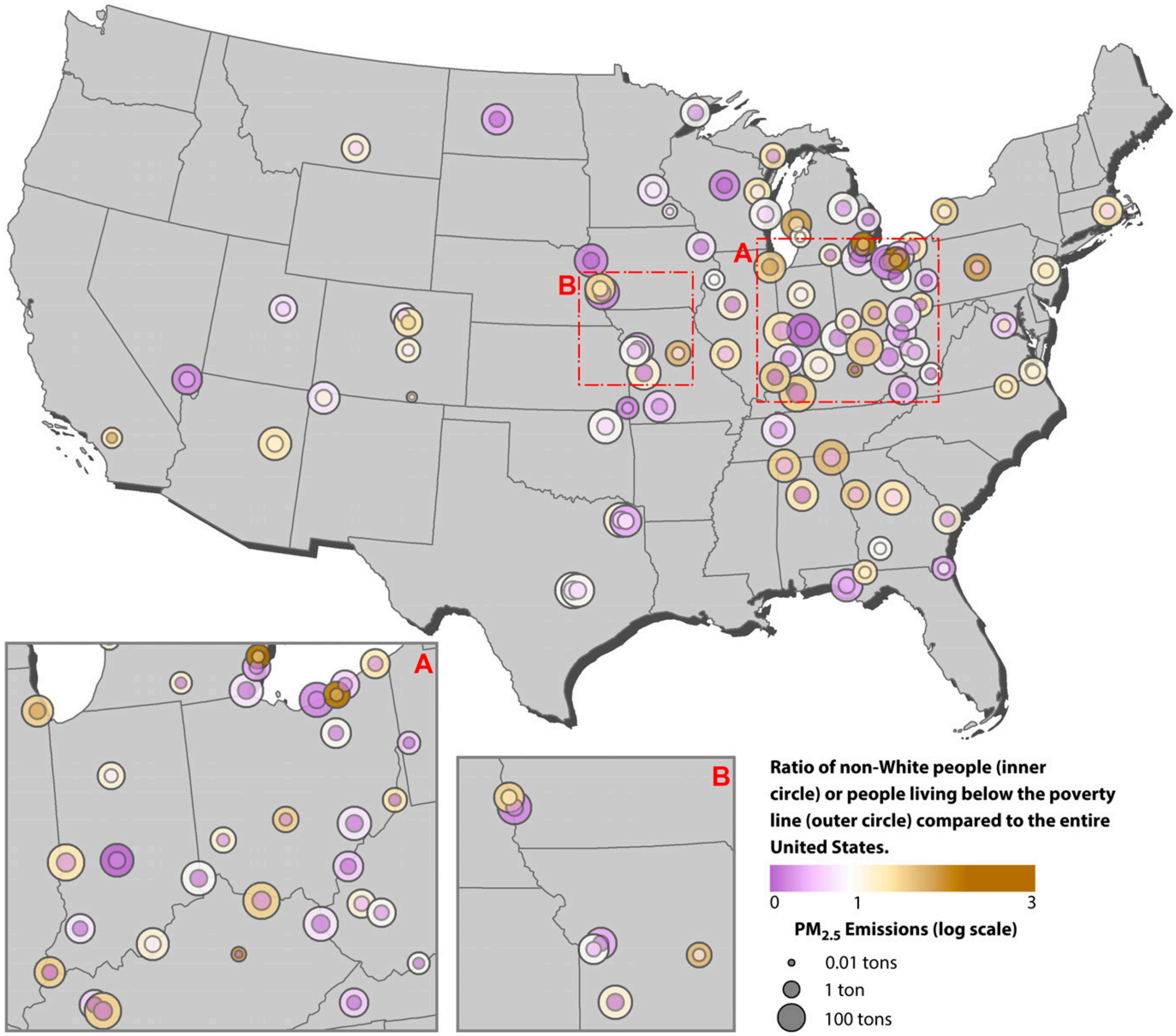
RESULTS

Among the 92 facilities with retired units, most were located in the Midwest, including a high concentration of facilities around the Ohio River and the Great Lakes (Figure 1). Eighteen percent of retired facilities were located in block groups in which the proportion of non-White individuals was greater than in the US population overall. In comparison, 38% of the US population is non-White according to the 2012 to 2016 ACS.[26] Fifty-one percent of retired facilities were located in block groups in which the proportion of individuals living below the poverty line was greater than in the US population, whereas 15% of the US population lives below the poverty line according to the 2012 to 2016 ACS results.

Omission of the 92 retired EGU_{cf}s decreased the block group–level absolute burden attributable to EGU_{cf}s in the total population by 8.6%, from 4.09 tons per year to 3.74 tons per year (Table A, available as a supplement to the online version of this article at http://www.ajph.org). The absolute burden also fell for every subgroup after omission of these facilities. The largest decrease in absolute burden occurred in the White subgroup (an 11% reduction, to 3.66 tons per year). A smaller reduction was observed for the non-White subgroup (5.0%, to 3.87 tons per year). Within the non-White subgroup, smaller reductions were observed for the Hispanic (4.4%, to 3.49 tons per year) and Black (6.6%, to 3.59 tons per year) subgroups. However, the 2014 absolute burdens for these subgroups were lower than those for the White subgroup. Absolute burdens decreased for the above- and below-poverty subgroups by 8.5% (to 3.67 tons per year) and 8.8% (to 4.15 tons per year), respectively. Consequently, the proportional burden decreased slightly, by 2.4%, among the White subgroup (to 0.98) while increasing among the non-White (3.9%, to 1.03), Hispanic (4.5%, to 0.93), and Black (2.2%, to 0.96) subgroups (Table B, available as a supplement to the online version of this article at http://www.ajph.org). Changes in proportional burdens were less than 1% for both the above-poverty (to 0.98) and below-poverty (to 1.11) subgroups.

Absolute and proportional burdens were compared through Monte Carlo simulations of random facility closures (Figure 2). After omission of the 92 retired EGU_{cf}s (among 1880 total facilities), the absolute burden for the overall population was below the average absolute burden predicted from the Monte Carlo simulations. The absolute burdens for the White and Black subgroups and for both income subgroups also fell below the average absolute burden from the simulations. Monte Carlo subgroup-level changes in absolute burden often led to greater disparities in proportional burdens among subgroups. Proportional burdens were above the upper 95% CI in the Monte Carlo analysis for the non-White subgroup, close to the upper 95% CI for the Hispanic subgroup, and below the lower 95% CI for the White subgroup. Results among poverty subgroups showed fewer differences from the Monte Carlo simulations.

Stratified analyses revealed patterns in how EGU_{cf} closures would influence burdens among populations living close to the facilities (Figure 3 and Table C, available as a supplement to the online version of this article at http://www.ajph.org). Absolute burdens were 2.69 tons per year for block groups in the White–nonpoverty stratum and 3.88 tons per year for block groups in the White–poverty stratum. For these strata, retirement of EGU_{cf}s resulted in an 18% to 33% reduction in absolute burden from 2014 to 2017 and a 70% to 72% reduction from 2008 to 2017. The absolute burden was 3.12 tons per year for block groups in the non-White–nonpoverty stratum. Notably, the absolute burden was lower for both the Black–nonpoverty and Hispanic–nonpoverty strata than for the non-White–nonpoverty stratum. For block groups in the non-White–poverty stratum, the absolute burden was 4.03 tons per year after closure of the EGU_{cf}s. These closures resulted in a 1.4% to 4.2% reduction in the absolute burden from 2014 to 2017 and a 52%



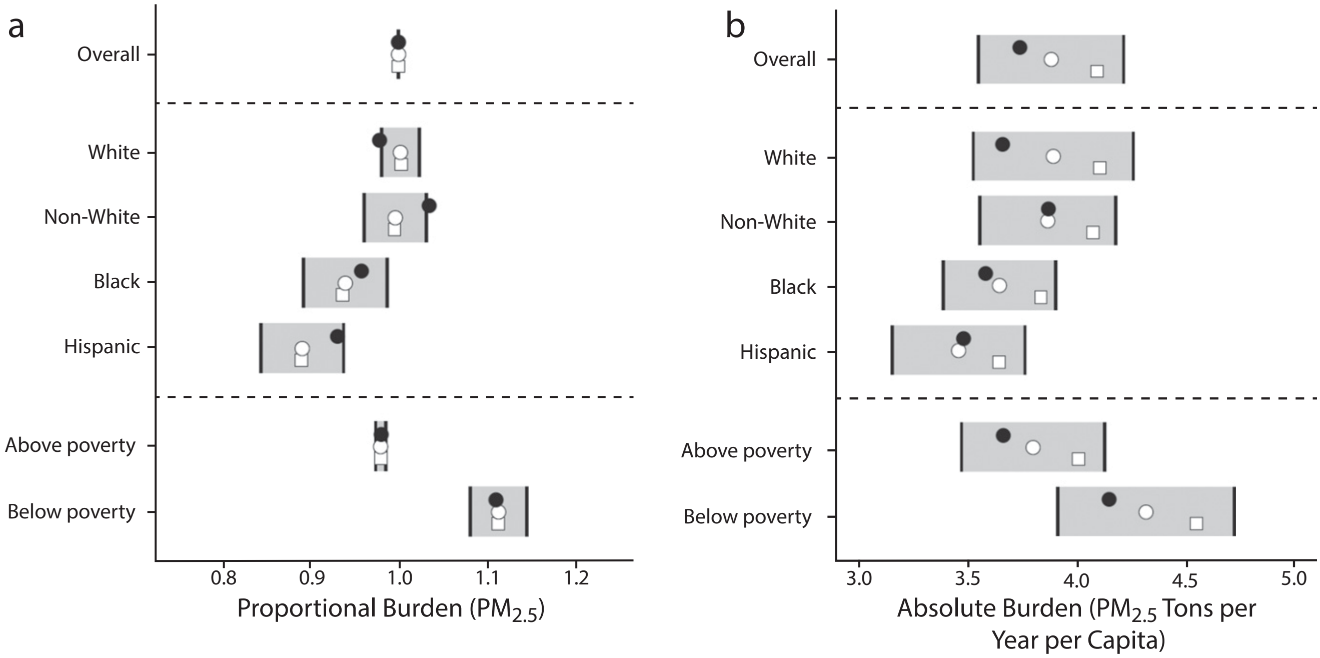
Note. Close-ups are provided for areas with numerous plants in Indiana, Ohio, and parts of Illinois, Michigan, Pennsylvania, Kentucky, West Virginia, and Virginia (A) and for parts of Nebraska, Kansas, Iowa, and Missouri (B). Each circle represents 3 pieces of information. The size of the outer circle (shown below the map) is related to the fine particulate matter (PM2.5) emissions of each facility on a log scale. The color of the inner circle (given by the color bar below the map) represents the ratio between the percentage of non-White people assigned to the facility via the centroid containment method and the overall percentage of non-White people in the United States (38%). The color of the outer circle represents the ratio between the percentage of people living below the poverty line assigned to the facility via centroid containment and the overall percentage of people in the United States living below the poverty line (15%). For both race/ethnicity and poverty, a ratio of 1 (shown in white) means that the population matches the overall composition of the US population. Only the continental United States is shown because no facilities were retired in Alaska or Hawaii during the study period.

FIGURE 1—Spatial Distribution of Coal-Fired Electricity-Generating Units That Were Retired Between 2015 and 2017: United States

to 74% reduction from 2008 to 2017 for non-White subgroups. The absolute burden was nearly identical for the non-White–poverty and Hispanic–poverty strata, especially during 2011 to 2017. However, for the Black–poverty stratum, the burden decreased from 13.40 tons per year in 2008 to 4.84 tons per year in 2017, a 64% reduction. From 2014 to 2017, closures resulted in a 6% reduction in the absolute burden.

DISCUSSION

The overall reduction in the absolute $PM_{2.5}$ burden attributable to fossil fuel emissions for the entire US population (Figure 2) suggests that reduced EGU_{cf} operations benefit every segment of the population by reducing premature mortality attributable to $PM_{2.5}$.[5–11] Still, changes in absolute burdens for each subgroup suggest that reductions have been greater among those living above the poverty line and among



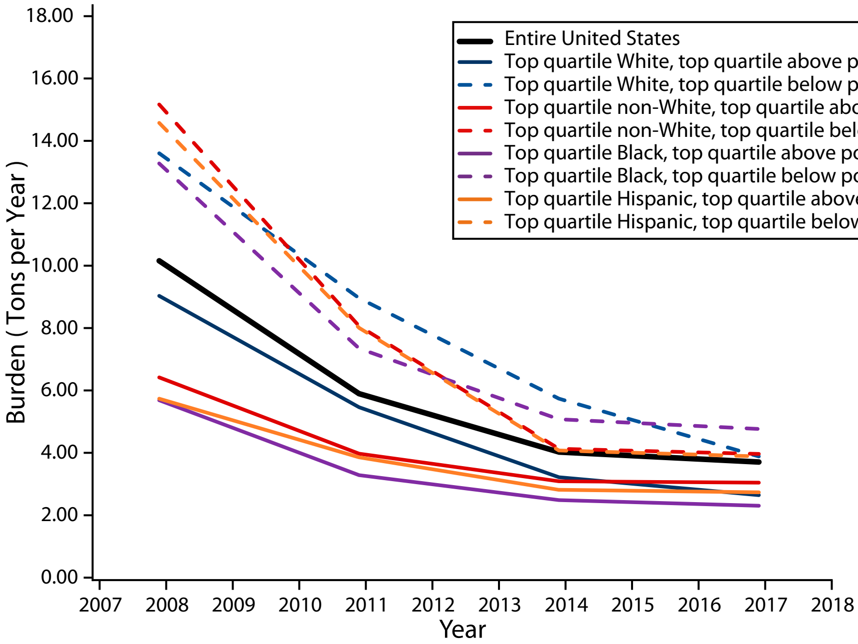
Note. $PM_{2.5}$ = fine particulate matter. Absolute burdens from coal-fired electricity-generating units (EGU_{cf}s) in 2014 data (squares) and burdens calculated after omission of emissions from 92 EGU_{cf}s that retired operations between 2015 and 2017 (solid circles) are displayed in comparison with mean burdens from a Monte Carlo analysis in which 92 facilities were omitted at random (open circles). Also shown are 95% confidence intervals for the Monte Carlo simulations (gray boxes bounded by black lines).
Source. US Environmental Protection Agency[27] and US Census Bureau.[26]

FIGURE 2—Comparison at the Average Block Group Level for the Total Population and for Race/Ethnicity and Poverty Strata of Nationwide (a) Proportional and (b) Absolute $PM_{2.5}$ Burdens (Tons per Year per Capita) Attributable to Fossil Fuels: United States, 2012–2016

White individuals, although the reductions observed were not significantly different from the cases in which facilities were retired at random (Figure 1). In the nationwide analysis, the difference in absolute burden was largest for the below- and above-poverty subgroups, and that difference did not change between 2014 and 2017. Disparities between proportional burdens in below- and above-poverty subgroups were unchanged, with a 13% higher proportional burden for the below-poverty subgroup in both 2014 and 2017. Mikati et al.[4] and Mohai et al.[1] also observed higher burdens for all $PM_{2.5}$ sources among those below the poverty line compared with those above the poverty line.

Without regard to poverty status, the White subgroup was estimated to have benefited more from reduced EGU_{cf} operations than the non-White subgroup, with the absolute burden well below the central estimate for the Monte Carlo analysis. This finding is consistent with the results of other studies examining the role of race and ethnicity in disproportionate exposure to environmental hazards.[1,2,4,29] However, absolute burdens for the Black and Hispanic subgroups attributable to fossil fuel combustion were lower than the absolute burden for the White subgroup in 2014 and continued to be lower after retirement of EGU_{cf}s. Part of the reason for the difference between the non–White subgroup and the Black and Hispanic subgroups may be that the non-White category also encompassed Asian, American Indian/Alaska Native, Native Hawaiian and Other Pacific Islander, and other racial groups (in total, these subgroups accounted for 22% of the non-White subgroup). The other races subgroup could have included individuals of 2 or more races as well as nonrespondents, adding uncertainty to the absolute burden estimates for the Black and Hispanic subgroups. It was surprising that the Black subgroup did not account for a larger share of the absolute burden given that this subgroup was found by Tessum et al.[18] to have the largest exposure to $PM_{2.5}$ from EGU_{cf}s emissions.

Relative to the absolute burden calculations, a comparison of the 2017 proportional burden estimates with the Monte Carlo analysis suggests that the closures might not have been random but instead were influenced by communities' racial makeup, with the non-White subgroup potentially bearing an increased $PM_{2.5}$ burden. The 2017 proportional burden was found to fall below the 95% CI of the Monte Carlo analysis for the White subgroup. At the same time, the proportional burden increased beyond the 95% CI of the Monte Carlo analysis for the non-White subgroup and almost increased beyond the 95% CI for the Hispanic subgroup. The proportional burden increased slightly for the Black subgroup but not beyond the Monte Carlo 95% CI. The proportional burden for 2014 emissions data was less than 1% lower for the non-White subgroup than for the White subgroup. Conversely, the burden was nearly 6% higher for the non-White subgroup after omission of EGU_{cf}s with reduced operations. Such increases in proportional burden suggest that the burden of EGU_{cf}-related $PM_{2.5}$ emissions may be shifting toward non-White subgroups. As differences between proportional burdens in the White subgroup and each



Note. $PM_{2.5}$ = fine particulate matter. Data from 2008, 2011, and 2014 were derived from the National Emissions Inventory.[27] We estimated 2017 values by omitting from our analysis coal-fired electricity-generating units that retired operations between 2015 and 2017.

FIGURE 3—Trends in Absolute Burdens due to $PM_{2.5}$ Emitted by Fossil Fuels: United States, 2008–2017

non-White subgroup increased with reductions in EGU_{cf} operations, inequities in burdens appeared to grow.

The stratified analyses shed further light on changes in absolute burdens based jointly on race/ethnicity and poverty status. Unsurprisingly, burdens were greater in the poverty strata than the nonpoverty strata regardless of race, although disparities in $PM_{2.5}$ absolute burdens both within and between the poverty strata and the nonpoverty strata diminished over the 9-year period. The higher absolute burden for the Black–poverty stratum than for the White–poverty, non-White–poverty, and Hispanic–poverty strata indicates that the Black–poverty stratum assumed a greater share of the burden after the 92 EGU_{cf}s were removed from the analysis. This was not evident in the Monte Carlo simulations, because the data were not broken down by both race/ethnicity and poverty status. Differences among the non-White–poverty, Hispanic–poverty, and White–poverty strata's absolute burdens were small in 2017 and therefore should not be overinterpreted in the absence of data from future years.

Our findings suggest that place-based characteristics such as demographic community makeup are important determinants of burden. The White subgroup had a higher absolute burden than did the Black subgroup within the non-White–nonpoverty stratum and a higher absolute burden than did the Hispanic subgroup within the non-White–poverty stratum. Likewise, the Black subgroup had the lowest absolute burden of any subgroup within the Black–poverty stratum, although that stratum had the highest absolute burden among the race/ethnicity–poverty strata investigated. Mikati et al.[4] investigated absolute burdens from all US $PM_{2.5}$ emissions for different rural–urban commuting area classifications and found similar levels of absolute burden among most race/ethnicity and poverty subgroupings within these classifications but dissimilarities among the classifications themselves. These findings support the conclusion that those living in non-White or impoverished communities are at higher risk, regardless of individual characteristics.

Limitations and Strengths

A limitation of this study is that when EGU_{cf}s appeared in Energy Information Administration reports, we assumed that their operations were fully retired. It is likely that some facilities continued operations at a reduced level. If so, the reductions in absolute burden described here would have been overestimated, and the 2017 absolute burden values would have been underestimated. The true absolute burden values estimated for 2017 on the basis of EGU_{cf} retirements would be somewhere between the burdens computed with the 2014 NEI data and the values presented for 2017. In addition, the NEI data were coded according to the North American Industry Classification System, which groups all fossil fuels together (i.e., coal, petroleum coke, petroleum liquids, natural gas). Therefore, comparisons of absolute burden from 2008, 2011, and 2014 may have been inflated, and the percentage reductions in absolute burden may have been underestimated relative to an analysis drawing only from EGU_{cf}s. However, given that EGU_{cf}s and petroleum-fueled EGUs have been largely supplanted by cleaner-burning and cheaper natural gas generators, the error in absolute burden would be anticipated as small.[30] A strength of our study is its insight into the interaction of race/ethnicity and poverty with absolute burden, particularly in the context of US utilities replacing coal with natural gas.[30]

Public Health Implications

Our results suggest that state and local policymakers responsible for implementation of air quality management under the Clean Air Act should consider place-based characteristics in a wider strategy to effect decisions that jointly promote equity and reduce $PM_{2.5}$ emissions. For example, the Government Code of the State of California was amended in 2016 to require that local planners identify policies seeking to improve environmental quality in communities that have experienced disproportionate impacts of environmental pollution.[31] Local planners in California can comply with this code in part by using our burden analysis technique as a basis for recommending which EGU_{cf}s should be prioritized for emissions reductions to determine scenarios that reduce inequities in the burden due to EGU_{cf}-related $PM_{2.5}$ emissions before policies are implemented. More generally, policymakers can stratify emissions burdens by the socioeconomic and demographic characteristics of geographically defined communities to allow comparisons of different scenarios. This type of detailed analysis can then provide a data-driven foundation[32] for local policymakers to hold discussions that engage affected community members and environmental justice organizations to make equitable decisions with regard to air pollution sources. AJPH

CONTRIBUTORS

J. Richmond-Bryant originated the study, contributed to the statistical analysis, and drafted the article. I. Mikati originated the study, contributed to the statistical analysis, and edited the article. A. F. Benson performed the geographic information systems analysis and produced the map. T. J. Luben and J. D. Sacks provided consultation throughout the study and edited the article.

ACKNOWLEDGMENTS

This study was supported in part by the Research Participation Program of the US Environmental Protection Agency (EPA), administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the US Department of Energy and the EPA.

We thank Jennifer Nichols, Danelle Lobdell, Tara Greaver, and John Vandenberg for their helpful comments on the article.

Note. This document was reviewed in accordance with EPA policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the EPA.

CONFLICTS OF INTEREST

None of the authors report any conflicts of interest.

HUMAN PARTICIPANT PROTECTION

No protocol approval was needed for this study because no human participants were involved.

REFERENCES

1. Mohai P, Lantz PM, Morenoff J, House JS, Mero RP. Racial and socioeconomic disparities in residential proximity to polluting industrial facilities: evidence from the Americans' Changing Lives Study. *Am J Public Health*. 2009;99(suppl 3):S649–S656.

2. Clark LP, Millet DB, Marshall JD. Changes in transportation-related air pollution exposures by race-ethnicity and socioeconomic status: outdoor nitrogen dioxide in the United States in 2000 and 2010. *Environ Health Perspect*. 2017;125(9):097012.

3. Paolella DA, Tessum CW, Adams PJ, et al. Effect of model spatial resolution on estimates of fine particulate matter exposure and exposure disparities in the United States. *Environ Sci Technol Lett*. 2018;5(7):436–441.

4. Mikati I, Benson AF, Luben TJ, Sacks JD, Richmond-Bryant J. Disparities in distribution of particulate matter emission sources by race and poverty status. *Am J Public Health*. 2018;108(4):480–485.

5. Dockery DW, Pope CA III, Xu X, et al. An association between air pollution and mortality in six US cities. *N Engl J Med*. 1993;329(24):1753–1759.

6. Laden F, Neas LM, Dockery DW, Schwartz J. Association of fine particulate matter from different sources with daily mortality in six US cities. *Environ Health Perspect*. 2000;108(10):941–947.

7. Pope CA III, Burnett RT, Thurston GD, et al. Cardiovascular mortality and long-term exposure to particulate air pollution: epidemiological evidence of general pathophysiological pathways of disease. *Circulation*. 2004;109(1):71–77.

8. Krewski D, Burnett R, Jerrett M, et al. Mortality and long-term exposure to ambient air pollution: ongoing analyses based on the American Cancer Society cohort. *J Toxicol Environ Health A*. 2005;68(13–14):1093–1109.

9. Laden F, Schwartz J, Speizer FE, Dockery DW. Reduction in fine particulate air pollution and mortality: extended follow-up of the Harvard Six Cities study. *Am J Respir Crit Care Med*. 2006;173(6):667–672.

10. Lepeule J, Laden F, Dockery D, Schwartz J. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. *Environ Health Perspect*. 2012;120(7):965–970.

11. Di Q, Wang Y, Zanobetti A, et al. Air pollution and mortality in the Medicare population. *N Engl J Med*. 2017;376(26):2513–2522.

12. Nachman KE, Parker JD. Exposures to fine particulate air pollution and respiratory outcomes in adults using two national datasets: a cross-sectional study. *Environ Health*. 2012;11:25.

13. Basu R, Woodruff TJ, Parker JD, Saulnier L, Schoendorf KC. Comparing exposure metrics in the relationship between PM2.5 and birth weight in California. *J Expo Anal Environ Epidemiol*. 2004;14(5):391–396.

14. Bravo MA, Anthopolos R, Bell ML, Miranda ML. Racial isolation and exposure to airborne particulate matter and ozone in understudied US populations: environmental justice applications of downscaled numerical model output. *Environ Int*. 2016;92–93:247–255.

15. Bell ML, Ebisu K. Environmental inequality in exposures to airborne particulate matter components in the United States. *Environ Health Perspect*. 2012;120(12):1699–1704.

16. Gelobter M. Toward a model of environmental discrimination. In: Bryant B, Mohai P, eds. *Race and the Incidence of Environmental Hazards: A Time for Discourse*. New York, NY: Westview Press; 1992:64–81.

17. Nguyen NP, Marshall JD. Impact, efficiency, inequality, and injustice of urban air pollution: variability by emission location. *Environ Res Lett*. 2018;13(2):024002.

18. Tessum CW, Apte JS, Goodkind AL, et al. Inequity in consumption of goods and services adds to racial-ethnic disparities in air pollution exposure. *Proc Natl Acad Sci U S A*. 2019;116(13):6001–6006.

19. Henneman LRF, Choirat C, Ivey C, Cummiskey K, Zigler CM. Characterizing population exposure to coal emissions sources in the United States using the HyADS model. *Atmos Environ*. 2019;203:271–280.

20. Goodkind AL, Tessum CW, Coggins JS, Hill JD, Marshall JD. Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions. *Proc Natl Acad Sci U S A*. 2019;116(18):8775–8780.

21. Fann N, Baker KR, Fulcher CM. Characterizing the PM2.5-related health benefits of emission reductions for 17 industrial, area and mobile emission sectors across the US. *Environ Int*. 2012;49:141–151.

22. Levy J, Baxter L, Schwartz J. Uncertainty and variability in health-related damages from coal-fired power plants in the United States. *Risk Anal*. 2009;29(7):1000–1014.

23. US Energy Information Administration. Electric power monthly with data for December 2017. Available at: https://www.eia.gov/electricity/monthly/archive/february2018.pdf. Accessed February 5, 2020.

24. US Energy Information Administration. Electric power monthly with data for December 2016. Available at: https://www.eia.gov/electricity/monthly/archive/february2017.pdf. Accessed February 5, 2020.

25. US Energy Information Administration. Electric power monthly with data for December 2015. Available at: https://www.eia.gov/electricity/monthly/archive/february2016.pdf. Accessed February 5, 2020.

26. US Census Bureau. American Community Survey summary file data: 2012–2016 ACS 5-year estimates. Available at: https://www.census.gov/acs/www/data/data-tables-and-tools/data-profiles/2016. Accessed February 5, 2020.

27. US Environmental Protection Agency. 2014 National Emissions Inventory (NEI) data. Available at: https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data. Accessed February 5, 2020.

28. Boyce JK, Pastor M. Clearing the air: incorporating air quality and environmental justice into climate policy. *Clim Change*. 2013;120(4):801–814.

29. Mohai P, Saha R. Which came first, people or pollution? Assessing the disparate siting and post-siting demographic change hypotheses of environmental injustice. *Environ Res Lett*. 2015;10(11):115008.

30. US Energy Information Administration. Fuel competition in power generation and elasticities of substitution. Available at: https://www.eia.gov/analysis/studies/fuelelasticities. Accessed February 5, 2020.

31. State of California. California Government Code, Title 7, Division 1, Chapter 3, Article 5: authority for and scope of general plans. Available at: https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=GOV&division=1.&title=7.&part=&chapter=3.&article=5. Accessed February 5, 2020.

32. Minkler M. Linking science and policy through community-based participatory research to study and address health disparities. *Am J Public Health*. 2010;100(suppl 1):S81–S87.