AIR POLLUTION

Disparities in $PM_{2.5}$ air pollution in the United States

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Air pollution at any given time is unequally distributed across locations. Average concentrations of fine particulate matter smaller than 2.5 micrometers in diameter ($PM_{2.5}$) have fallen over time. However, we do not know how the spatial distribution of $PM_{2.5}$ has evolved. Here, we provide early evidence. We combine 36 years of $PM_{2.5}$ concentrations measured over ~8.6 million grid cells with geographic, economic, and demographic data from ~65,000 U.S. census tracts. We show that differences in $PM_{2.5}$ between more and less polluted areas declined substantially between 1981 and 2016. However, the most polluted census tracts in 1981 remained the most polluted in 2016. The least polluted census tracts in 1981 remained the least polluted in 2016. The most exposed subpopulations in 1981 remained the most exposed in 2016. Overall, absolute disparities have fallen, but relative disparities persist.

Fine particulate matter concentrations in the United States have declined by ~70% since 1981 (*1*, *2*). These improvements in air quality are associated with greater life expectancy, reduced infant mortality, higher property values, increased productivity, higher earnings, and other benefits (*3*–*11*). The existing literature documenting changes in air pollution over time focuses on concentrations averaged across locations. However, little evidence documents how the distribution of pollution concentrations has changed over time.

Air pollution in any given time period is unequally distributed over space (*12*). Particulate matter and other criteria air pollutants vary geographically because of differences in population density, emissions sources, economic activity, climate, and geophysical conditions (*13*). Pollution is associated with race, poverty, and demographic factors owing to sociopolitical forces, residential choice, and other influences (*12*, *14*, *15*). However, related scholarship does not systematically characterize how this spatial variation has evolved over time. We have limited information on whether policy or other factors have reduced pollution disparities across locations or whether such disparities persist through time.

Here, we provide evidence on how the spatial distribution of fine particulate matter smaller than 2.5 μm in diameter ($PM_{2.5}$) has changed over recent decades. To do this, we compile 36 years of annual $PM_{2.5}$ data from chemical transport modeling, satellite remote sensing, and ground-based measurements over ~8.6 million U.S. grid cells that measure 0.01° by 0.01° (0.9 km by 1.1 km) (*2*) (supplementary text, section S1). We focus on $PM_{2.5}$ because of its high morbidity and mortality risk, because of its disproportionate impact on the monetized benefits of federal regulation, and because newly available data provide fine-scale estimates spanning nearly four decades (*2*, *8*, *10*, *16*, *17*). We combine these $PM_{2.5}$ estimates with time-varying administrative, geographic, policy, and sociodemographic data for each of the ~65,000 census tracts in the contiguous United States (supplementary text, sections S2 and S3).

We first characterize how the distribution of $PM_{2.5}$ concentrations across U.S. census tracts changed between 1981 and 2016. Figure 1 documents a 69% decline in mean $PM_{2.5}$ between 1981 and 2016, consistent with (*1*, *2*). Figure 1 also illustrates that the gaps in $PM_{2.5}$ concentrations between more and less polluted census tracts narrowed considerably. The $PM_{2.5}$ concentration gap between the 90th and 10th percentiles was 15.66 μg/m^3 in 1981 and 4.16 μg/m^3 in 2016. $PM_{2.5}$ concentration gaps between census tracts with high and low fractions of disadvantaged subpopulations have generally, but not universally, narrowed over time as well (fig. S1).

The reductions in absolute disparities documented in Fig. 1 provide limited information on relative disparities across locations. We do not know whether locations that were historically the most polluted are still the most polluted. It is not clear a priori whether one might expect persistence or reversals in relative disparities (supplementary text, section S4). To explore the issue, we assign each census tract to a percentile of the distribution and examine the correlation between $PM_{2.5}$ percentile rank in 1981 and the average corresponding $PM_{2.5}$ percentile rank in 2016. Rank-rank comparisons are common for analyzing distributional changes over time and have statistical advantages (*18*). On average, we estimate a rank-rank correlation coefficient of 0.80 ($p <$ 0.01), indicating a very strong positive association between historical relative pollution and more recent relative pollution (table S1). The modal change in percentile rank between 1981 and 2016 was 0, the mean change was –0.00006, and the median change was –1 percentile point. On average, the least polluted census tracts in 2016 were the least polluted census tracts in 1981. On average, the most polluted census tracts in 2016 were the most polluted census tracts in 1981.

Figure 2 plots percentiles of census tracts according to $PM_{2.5}$ in 2016 (vertical axis) against $PM_{2.5}$ percentiles in 1981 (horizontal axis). First, we observe widespread relative rank preservation across the entire distribution. All percentile pairs lie near the 45° line, such that, on average, a census tract's $PM_{2.5}$ percentile rank in 2016 was similar to its $PM_{2.5}$ rank in 1981. Second, we observe modest median reversion. On average, a census tract with below-median $PM_{2.5}$ in 1981 experienced greater relative pollution in 2016, and a census tract with above-median $PM_{2.5}$ in 1981 experienced lower relative pollution in 2016. Third, the tails of the distribution are particularly stable. Values on the y

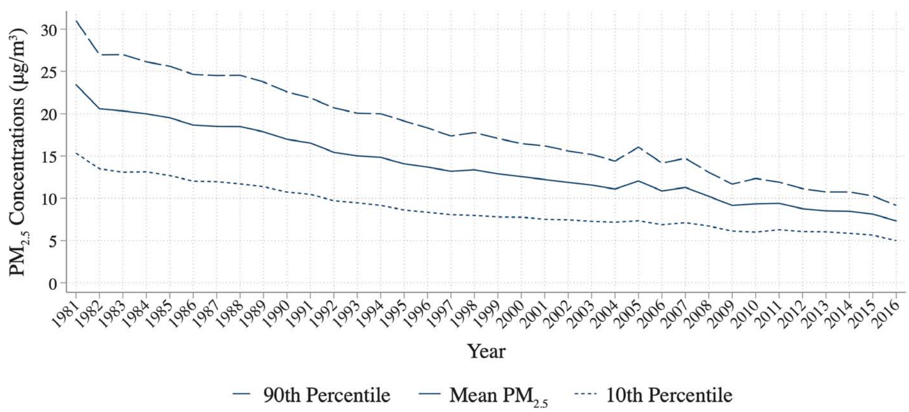

Fig. 1. Change in $PM_{2.5}$ concentrations between 1981 and 2016 in μg/m^3. We observe that mean $PM_{2.5}$ concentrations have fallen substantially over time, from 23.43 μg/m^3 in 1981 to 7.32 μg/m^3 in 2016, a reduction of 16.11 μg/m^3. In addition, we observe that the gap between the 90th and 10th percentiles has also shrunk. In 1981, the difference between the 90th and 10th percentiles was 15.66 μg/m^3. In 2016, the difference between the 90th and 10th percentiles was 4.16 μg/m^3. Gaps between the 90th and 10th percentiles are arbitrarily chosen but illustrative of broader patterns.

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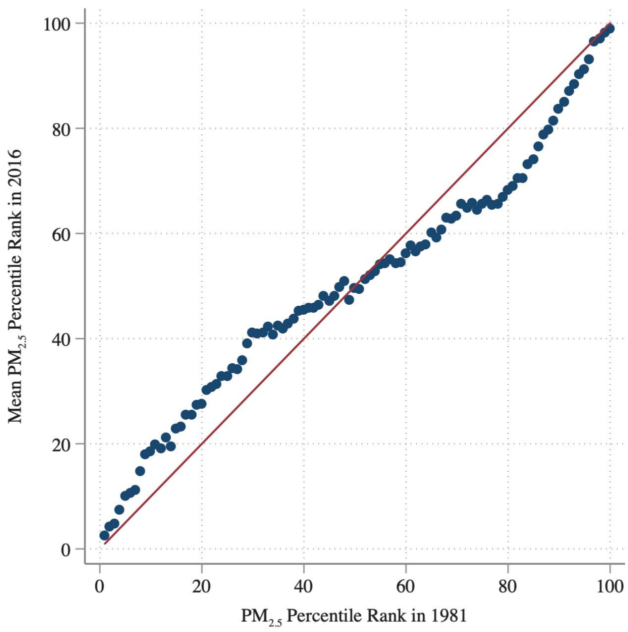

Fig. 2. Relationship between $PM_{2.5}$ rank in 1981 and $PM_{2.5}$ rank in 2016. The red line is the 45° line. If all points lay on the red line, this would indicate that there was no change in rank between 1981 and 2016; for example, a census tract at the 20th percentile of the $PM_{2.5}$ distribution in 1981 would also be at the 20th percentile of the $PM_{2.5}$ distribution in 2016. Deviations from the red line represent the average change in rank between 1981 and 2016. Points above the red line represent an increase in relative rank and a decrease in relative air quality. Points below the red line represent a reduction in relative rank and an improvement in relative air quality. The figure indicates that there is very high persistence in rank over time. The highest-rank locations in 1981 are the highest-rank locations in 2016. The lowest-rank locations in 1981 are the lowest-rank locations in 2016. Intermediate ranks experience some change; however, the average change is small and follows a pattern consistent with reversion to the median. Below-median *x*-axis values (1981 ranks) correspond to *y*-axis values (2016 ranks) above the 45° line, and above-median *x*-axis values (1981 ranks) correspond to *y*-axis values (2016 ranks) below the 45° line.

axis (2016 ranks) for particularly low and high 1981 ranks are systematically near the 45° line. Of the most polluted 5% of census tracts in 1981, 93.9% were among the most polluted 10% of census tracts in 2016. Of the least polluted 5% of census tracts in 1981, 89.7% were among the least polluted 10% of census tracts in 2016. These summary statistics are arbitrarily chosen but illustrative of broader patterns (fig. S2).

A possible explanation for the persistence in relative disparities across locations is that reductions in $PM_{2.5}$ were proportional. Figure 3A illustrates that $PM_{2.5}$ concentrations fell more in census tracts that were more polluted in 1981. However, larger reductions came from much higher baselines. Figure 3B indeed documents that observed $PM_{2.5}$ concentration reductions were approximately proportional across U.S. census tracts. The most polluted locations did not experience disproportional reductions in $PM_{2.5}$.

Our findings suggest that relative disparities persist for most U.S. census tracts. Nevertheless, it remains possible that aggregation obscures regional or local differences. Figure 4 summarizes the geographic distribution of changes in $PM_{2.5}$ percentile rank over time. The dominant message remains that relatively more polluted areas in 1981 were still more polluted in 2016 and relatively less polluted areas in 1981 were still less polluted in 2016. However, some local variation in rank change exists. Ohio, West Virginia, eastern Kentucky, and the Northeast Corridor became relatively less polluted. California's Central and Imperial Valleys, southwestern Arizona, southern Texas, and western Arkansas and eastern Oklahoma became relatively more polluted. Mechanisms for differential trends in these specific locations may include import competition, the decline in manufacturing, changes in the structure of energy production (e.g., the hydraulic fracking boom, a decline in coal production), and differential environmental regulation (*19*–*26*).

Our results are robust to population weighting, which rebalances the analysis to apply to the average American rather than the average U.S. census tract (table S1). From a socioeconomic and demographic perspective, the most exposed subpopulations also remain similar through time (fig. S3 and table S2). Census tracts' baseline 1981 black population shares, educational attainment, unemployment rates, and poverty rates are unrelated statistically to changes in rank between 1981 and 2016. More populated, whiter, higher income, and less Hispanic areas at baseline in 1981 are associated with reductions in rank over time. A 1-SD increase in a census tract's baseline 1981 population, white share, and income is associated with an average decrease of 1.77, 2.36, and 0.93 percentile rank points between 1981 and 2016. A 1-SD increase in a census tract's baseline 1981 Hispanic share is associated with an average increase of 3.92 percentile rank points between 1981 and 2016. Areas becoming more populated, poorer, more Hispanic, less white, and less educated between 1981 and 2016 are associated with increases in rank over time. A 1-SD increase in a census tract's growth in population, poverty rate, unemployment rate, and Hispanic share is associated with an average increase of 3.27, 1.98, 2.01, and 3.68 percentile rank points between 1981 and 2016. A 1-SD increase in a census tract's growth in income, educational attainment, and white share is associated with an average decrease of 1.60, 2.56, and 2.52 percentile rank points between 1981 and 2016. We caution that these are descriptive correlations, documenting differences across subpopulations.

We find somewhat larger associations between $PM_{2.5}$ percentile rank and market or regulatory factors (fig. S3 and table S2). A 1-SD decrease in a census tract's manufacturing employment share over time is associated with an average increase of 4.68 percentile rank points between 1981 and 2016. Census tracts in nonattainment with $PM_{2.5}$ ambient air-quality standards before 2016 are associated with an average decrease of 7.09 percentile rank points between 1981 and 2016.

We explore sensitivity. Our findings are robust to using alternative measures of relative disparities (table S3). Our results are not driven by differences in population density or urban-rural distinctions (fig. S4 and table S4). Our results are robust to comparisons within states; rank-rank correlations within each state range from 0.72 to 0.99 and average 0.91 (fig. S5 and table S5). Our results are robust to choosing comparison years other than 1981. Our approach generates conservative estimates (fig. S6). Our results are not sensitive to the choice of single years as points of comparison. Analyses using multiyear averages of $PM_{2.5}$ generate similar findings (fig. S7 and table S6). Correlations between changes in $PM_{2.5}$ percentile rank and socioeconomic and demographic factors are robust to using the rank of, and rank changes in, tract-level characteristics (fig. S8 and table S7). Our findings are robust to using pollution monitor data (figs. S9 and S10). Although $PM_{2.5}$ monitor data are only available between 2000 and 2016 for a comparatively small number of (mostly urban) locations, we estimate a rank-rank correlation coefficient of 0.79, which is statistically indistinguishable from our primary correlation coefficient. Last, our results are not sensitive to using different moments of the $PM_{2.5}$ distribution, including the median and each decile (10th through 90th percentile) (figs. S11 to S13 and table S8). Rank dependence is weaker when using annual maximum $PM_{2.5}$ concentrations, but we still estimate a correlation coefficient of 0.5 to 0.7.

We note caveats. First, we study the distribution of $PM_{2.5}$ across the contiguous United States. We do not inform distributional changes for other pollutants or other locations. Second, we study changes in the distribution of $PM_{2.5}$

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across locations; we do not observe individual-level pollution exposure. Our results are robust to population weighting. Third, our analysis is descriptive. We do not directly explore hypotheses related to demographic change (i.e., "moving to the nuisance" or "residential sorting") (*15*, *27*–*30*). In our aggregate analysis, changes in relative pollution are not strongly correlated with socioeconomic and demographic factors. We do not provide causal mechanisms for our empirical regularities.

In sum, we explore how the spatial distribution of $PM_{2.5}$ has changed in recent decades. We first document that absolute disparities are shrinking. Differences in $PM_{2.5}$ concentrations between more and less polluted census tracts declined between 1981 and 2016. All else equal, absolute differences between areas in particulate-induced morbidity, mortality, and earnings losses should be expected to decline (*3*–*5*, *7*, *8*, *10*, *11*). By contrast, we show that relative disparities in $PM_{2.5}$ concentrations across space are notably persistent. Areas that were more polluted in 1981 are still more polluted in 2016. Areas that were less polluted in 1981 are still less polluted in 2016. Fairness, equity, and justice are often inherently comparative, and

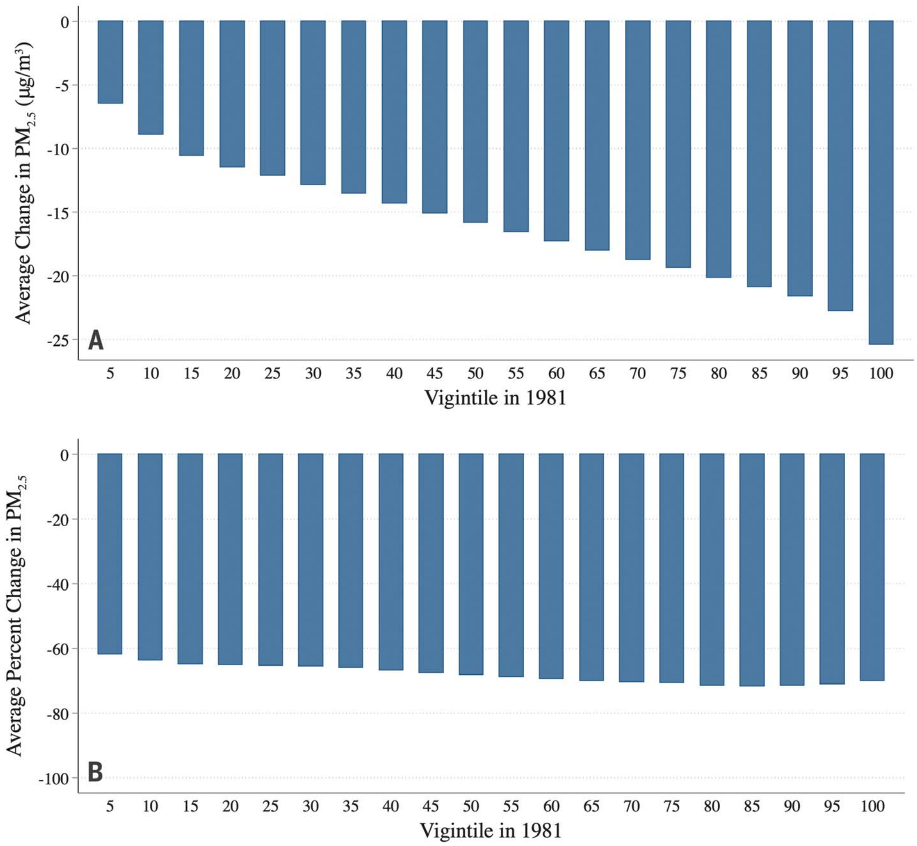

Fig. 3. Changes in $PM_{2.5}$ between 1981 and 2016 for each vigintile bin in 1981. (**A**) Reduction in $PM_{2.5}$ concentrations (μg/m^3) between 1981 and 2016 for each vigintile bin in 1981. We observe that the largest reductions in $PM_{2.5}$ concentrations were experienced in census tracts that were the most polluted in 1981. (**B**) Percent reduction in $PM_{2.5}$ concentrations between 1981 and 2016 for each vigintile bin in 1981. We observe that reductions in $PM_{2.5}$ were largely proportional throughout the distribution. The most polluted census tracts experienced approximately the same relative reductions in $PM_{2.5}$ as the least polluted census tracts.

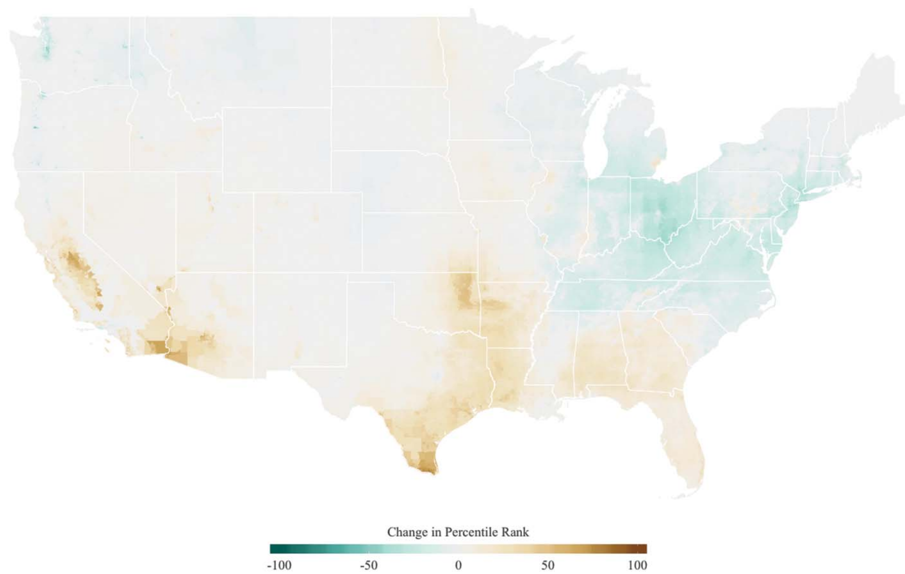

Fig. 4. Map of the change in $PM_{2.5}$ rank between 1981 and 2016 for each census tract in the contiguous United States. Green represents tracts where the rank has declined over time. Brown represents tracts where the rank has increased over time. Darker shades represent greater absolute changes. Most census tracts have experienced small changes in rank. The modal change is 0, the mean change is −0.00006, and the median change is −1. Ohio, West Virginia, eastern Kentucky, and the Northeast Corridor became relatively less polluted. California's Central and Imperial Valleys, southwestern Arizona, southern Texas, and western Arkansas and eastern Oklahoma became relatively more polluted.

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these types of relative disparities are important for normative aspects of social welfare (*31*). In this sense, we build on the growing literature documenting relative disparities in income, health, and other contexts (*32*–*37*). We also illustrate that changes in relative $PM_{2.5}$ concentrations are not strongly correlated with socioeconomic and demographic factors. If anything, relative disparities are growing for vulnerable subpopulations. From a socioeconomic and demographic perspective, the most exposed subpopulations to fine particulate matter remain constant over time.

We do not attempt a formal welfare analysis. Nevertheless, environmental justice and reducing disparities have been stated objectives of U.S. environmental policy for decades (*12*, *14*, *15*). U.S. Environmental Protection Agency and state guidelines aim for all people to enjoy the same degree of protection from environmental hazards and stipulate that no groups should bear a disproportionate share of pollution. Although absolute $PM_{2.5}$ disparities have fallen substantially over the past four decades, relative disparities persist.

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SUPPLEMENTARY MATERIALS

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Supplementary Text
Figs. S1 to S13
Tables S1 to S8
References (*39*–*55*)

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Cleaner skies

Particulate air pollution in the contiguous United States has decreased considerably over recent decades, but where exactly has that progress been made? Colmer *et al.* analyzed 36 years of data and found that the spatial distribution of fine particulate matter concentrations has remained largely unchanged over that interval (see the Perspective by Ma). Although, fine particulate pollution levels have dropped overall, those areas that were most and least polluted in 1981 remain so today. We may have made important strides in pollution control, but we have been less successful in addressing disparities of exposure between communities.

Science, this issue p. 575; see also p. 503

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