Regional and county flows of particulate matter damage in the US

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Abstract
Despite several decades of declining emissions, the health costs of particulate matter (PM$_{2.5}$) in the US remain substantial, with more than $1$ trillion in annual damages. We analyze the inter-county impacts of PM$_{2.5}$ for 2008, 2011, and 2014 and find that even though emissions from point sources have fallen over this period, the share of PM$_{2.5}$ attributable to pollution transported across county and state boundaries is still considerable in many localities. Importantly, the benefits of reduced emissions are not uniformly distributed nationwide, with 26% of counties—concentrated in the South, Midwest, and Pacific Northwest—experiencing worsening health damages since 2008. Around 30% of all US counties receive 90% of their health damages from emissions in other counties, and these damage-importing counties also tend to have lower median incomes. Our results support continued state and federal cooperation to meet air quality standards and reduce the damages caused by PM$_{2.5}$ from transported air pollution.

1. Introduction

In the US, uniform National Ambient Air Quality Standards (NAAQS) are set by the federal Environmental Protection Agency (EPA), while states and more granular levels of government are typically charged with implementing and, in most cases, enforcing the standards. However, even as US emissions have decreased—sulfur-dioxide emissions fell by roughly 55% between 2008 and 2014 due to a combination of market forces and public policies [1–3]—the federal role in regulating air pollution has been questioned. For example, the EPA has proposed to relax federal emissions standards required by the New Source Review Program, and also recently denied petitions by Delaware and Maryland to require emissions reductions by upwind states that the petitioners argue are affecting their air quality [4, 5].

The role of the federal government in regulating air pollution reflects a principle of environmental policy design, namely that the appropriate authority lies with the level of government whose jurisdiction encompasses the geographic reach of the regulated pollutant. It is well known that the geographic reach of air pollution may extend well beyond the jurisdiction where the pollution is emitted [6–9] and often across state boundaries. The ‘good neighbor’ provision of the Clean Air Act requires states to consider the impact of their emissions on the ability of downwind states to meet their obligations to federal standards [10]. Although there is a substantial literature on the contribution of different sectors to health damages [3, 11–13], the spatial heterogeneity of how such damages are caused [14–18], and the implications of specific emissions reductions or policy interventions [19–24], as well as some explorations of municipal and interstate pollution transfers in the US [25–28], and international pollution transfers [29, 30], there has been no comprehensive assessment of inter-county particulate matter pollution and health impacts in the US.

In this study we use a reduced complexity air quality model to quantify recent trends in inter-county and regional flows of air pollution over the continental US. Specifically, we focus on how these flows affect annual mean concentrations of PM$_{2.5}$, which are subject to federal air quality standards. There is strong evidence that chronic exposure to increased ambient PM$_{2.5}$ concentrations is associated with adverse health effects, most significantly premature mortality from cardiopulmonary and respiratory illness [31–35], and globally PM$_{2.5}$ is estimated...
to be responsible for 95% of deaths related to ambient air pollution [36]. Chronic exposure to elevated PM$_{2.5}$ concentrations was estimated to have caused 130 000–200 000 premature deaths in the US in 2005, roughly 5%–7% of all deaths [37–39]. While PM$_{2.5}$ can be directly emitted, in most areas of the US the majority is formed from precursor pollutants such as sulfur-dioxide and nitrogen oxides in the atmosphere [40].

Our analysis uses an integrated assessment model (AP3, an updated version of the AP2 model [14, 15]) that combines emissions data with reduced complexity air quality modeling to assess particulate matter concentrations, population exposure, and subsequently health effects via increased risk of premature mortality. Although reduced complexity models are less spatially and temporally granular than full scale chemical transport models (CTMs) and include simplified air quality modeling, they have been shown to exhibit only modest losses in fidelity when predicting annual pollution concentrations, with differences that are comparable to the differences between CTMs or between CTMs and observed ambient concentrations when modeling at a county level [36, 41]. Given that, we use the AP3 model for this analysis because of its ability to capture the flows of emissions and health damages at an annual level—the focus of this analysis—as well as its ability to analyze multiple years of emissions data and sensitivity analyses in a way not possible with full-scale transport models [15, 41].

We assess the magnitude and impacts of inter-county and regional PM$_{2.5}$ pollution in 2008, 2011, and 2014; we choose these years based on data availability and to assess PM$_{2.5}$ levels before and after the Great Recession. We compute the share of health impacts in each country and region related to such flows and the relationship of such impacts to the race and income of county residents. Specifically, we quantify damages in a county as a result of its own emissions (‘self-inflicted’), from outside sources (‘imports’), as well as the damage caused in other counties by its emissions (‘exports’).

2. Methods

2.1. Overview of the AP3 model

We use AP3, an integrated assessment model developed to estimate monetary damages from emissions in the continental United States. AP3 is an updated version of the previously developed APEEP and AP2 models [15, 16]. Previous research has found that mortality accounts for approximately 95% of total monetized health damages and is largely driven by changes in annual PM$_{2.5}$ [3]; accordingly, in this analysis we focus only on the mortality effects from increased annual PM$_{2.5}$ concentration and do not include morbidity or other environmental damages. Although ozone is an important air pollutant to consider in certain locations, historically ozone-attributable mortality is on the order 3%–5% of that caused by PM$_{2.5}$ in the U.S [37, 38]. However, recent work suggests that the relative health impacts of ozone may rise as emissions from major point sources are reduced, and that a larger share of ozone impacts may occur across state lines relative to PM$_{2.5}$ [28]. We focus primarily on PM$_{2.5}$ in this study, but suggest continued research on the inter-jurisdictional impacts of other pollutants such as ozone going forward.

AP3 takes as input annual emissions of PM$_{2.5}$ as well as pollutants that are precursors to PM$_{2.5}$, including sulfur dioxide (SO$_2$), nitrogen oxides (NO$_x$), ammonia (NH$_3$), and volatile organic compounds (VOCs) from both anthropogenic and biogenic sources. To translate emissions into concentrations, the model simulates atmospheric transport, chemical transformation of precursors, and deposition across all US counties through a source-receptor matrix framework. Details on how AP3 models chemistry and transport can be found in supplementary information (SI) section A (available online at stacks.iop.org/ERL/15/104073/mmedia). Although the dispersion model employed by AP3 simplifies the complex mechanisms dictating the fate and transport of emissions, previous work has found that this modeling approach provides comparable results relative to other modeling approaches [41]. We compare annual PM$_{2.5}$ concentration estimates from AP3 to observed concentrations from EPA monitors and find error levels similar to those of CTMs; see SI section B for model performance and evaluation.

After translating emissions into concentrations, the next step is to compute exposures using county-level population estimates. Exposure is then translated to health effects using baseline all-cause mortality rates and estimates for the concentration-response function relating PM$_{2.5}$ concentration and increased mortality. We use a concentration-response function relating average annual PM$_{2.5}$ concentration to mortality from Krewski et al for adults over 30 years old and from Woodruff et al for infants less than 1 year old [34, 35]. In addition, we test the sensitivity of our results to other concentration-response estimates from the literature. Because the American Cancer Society study only included participants over 30 years of age, we do not estimate mortality effects for individuals between 1 and 30 years old. The concentration-response functions provide total estimates of the health damages incurred over time from a year of exposure to PM$_{2.5}$. Finally, the increased risk of mortality is valued using a Value of Statistical Life (VSL) applied uniformly to all age groups [42]. We use the EPA recommended VSL of $7.4$ million in USD 2006, or approximately $8.7$ million after adjusting for inflation using the consumer price index (CPI) to 2014 dollars. We test the sensitivity of the results to a range of values. An equation
summarizing the total damage calculation in AP3 can be found in SI section C.

2.2. Data sources
Data on emissions is taken from the EPA’s National Emissions Inventory (NEI), which provides a comprehensive accounting of emissions from all sectors for 2008, 2011, and 2014 [1]. We use total annual emissions of SO₂, NOₓ, direct PM₂.₅, NH₃, and anthropogenic and biogenic VOCs from all point, non-point, and mobile sources (on- and off-road).

Emissions from power plants and industrial activity (‘point’ sources) are reported by unit or facility, while non-point and mobile emissions (‘area’ sources) are reported at the county level. Although point source emissions are typically monitored, area source emissions—such as those from agriculture, transportation, and other dispersed emissions—are estimated or modeled by the EPA or state, local, or tribal agencies. As such, these emissions estimates may deviate from reality, subsequently resulting in mismeasurement of air quality and health damages. Despite this limitation, the NEI estimates represent the best existing approximation of county-level emissions in the continental US Summaries of total emissions and emissions by sector and state can be found in SI section D.

County-level population estimates used for assessing exposure are taken from the US Census American Community Survey (ACS), whereas the mortality data used in the concentration-response function is derived from the CDC National Vital Statistics System Multiple Cause of Death Dataset. Population and mortality data are binned into 19 age groups separated by five-year increments; see SI section D for additional details on these data sets.

2.3. Estimating import and export metrics
We employ a marginal approach to isolate the flows of damages into and out of specific counties. To do this, we first use the model to calculate baseline damages incurred by every county using all emissions. Next, we select a single and set its emissions to zero. We then re-run the model, assessing new annual average PM₂.₅ concentration values the damages occurring in each county. By comparing these two damage vectors, we can assess the following three measurements of flows of damages with relation to each county. We use this marginal damage approach to estimate three transport metrics:

1. Imported damages: damages occurring in county x that occur because of emissions from outside county x.
2. Exported damages: damages occurring in other counties that occur because of emissions inside county x.
3. Self-inflicted damages: damages occurring within county x as a result of emissions from that same county.

By iterating across all counties, we estimate these three metrics for each of the over 3000 counties in the continental US. A schematic illustrating this modeling process and the mathematical formulations for these calculations is provided in SI section C. We also use the source-receptor matrix in this calculation to aggregate these calculations to the state and regional levels.

To evaluate the relative magnitude of exports and imports, we also compute the export/import ratio for each county. This ratio helps to normalize comparisons across counties of different size, providing insight into the magnitude of each of the three types of damages relative to the other two. An export/import ratio of 0.25, for example, implies that a county incurs four deaths annually from emissions outside its borders for every death that it causes elsewhere. Analysis on the other two ratios (export/self-inflicted damages and import/self-inflicted damages) can be found in SI section J.

Since the VSL features in the numerator and the denominator, conclusions drawn from analysis of the ratios are independent from the assumption for VSL. In this work we focus primarily on analysis of the ratio of exports to imports; information and statistics on the other two ratios can be found in the SI. Although estimates of the distribution of source-receptor values based on many years of weather data would provide quantification of the uncertainty in the ratio estimates and other results related to damages from transported emissions, deriving such distributions is computationally expensive. The analysis in this work is intended to provide a framework for attributing damages across jurisdictions, and future research should explore new ways of quantifying the uncertainties associated with those estimates.

2.4. Sensitivity analysis
To understand how changes in population, mortality rates, and emissions are driving changes in damages over time, we also run our analyses using combinations of values for each of these three variables from each year of the study; as an illustration, we test 2014 level emissions with 2008 level population and mortality levels to see how damages change when only one factor is changed. We also conduct sensitivity to changes in marginal damages over the time of the study, finding that marginal damages have largely increased from 2008 to 2014, thus raising damages. Finally, we conduct a sensitivity analysis on some of the key input assumptions to the model, including the concentration-response coefficient, the choice of VSL, and valuation by life-years saved (i.e. employing
a VSLY approach). These sensitivity analyses are discussed below and in SI section E.

3. Results

3.1. Health damages over time

Figure 1 (a) shows estimates of annual US health damages by source type from PM$_{2.5}$ related deaths based on emissions levels from 2008, 2011, and 2014; damages for 2008 thus refer to the amount of annual damages attributable to 2008-level emissions. These damages come from exposure to PM$_{2.5}$ that is either directly emitted or produced by atmospheric reactions from precursor pollutants; these emissions are shown in figure 1(b).

From 2008 to 2014, total annual health damages have fallen both in absolute terms and relative to GDP (figure 1(a)), even as the average marginal damage from emissions of various pollutants has risen over that time period (figure 1(c)). This increase in marginal damages is a result of a combination of population growth and changes in atmospheric composition (see SI section F for average marginal damages and discussion). Figure 1(a) presents damages under baseline assumptions for VSL and concentration-response function, as well as high and low estimates based on a plausible range for those inputs (see sensitivity analysis in SI section E).

Total annual damages from emissions fell by approximately $200 billion from 2008 to 2014 (an 11% decrease), with essentially all of the decline occurring between 2008 and 2011. This decrease in damages reflects a transition from 166,000 to 143,000 annual deaths from PM$_{2.5}$ exposure, or 23,000 fewer deaths annually. For comparison, mean estimates of annual deaths from PM$_{2.5}$ from previous study were on the order of 100,000 to 200,000 when considering 2005 level emissions [28, 37, 38], which one study estimating a comparable reduction of 20,000 deaths between 2005 and 2011 [28]. Approximately 15,000 of the total number of annual deaths in each year are estimated to come from biogenic sources such as trees, vegetation, and soils. Furthermore, 60% of deaths occur in individuals 70 years or older; this is driven by the fact that PM$_{2.5}$ exposure is a risk multiplier, meaning that populations with high baseline mortality rates incur the highest health consequences. Even as total PM$_{2.5}$ deaths decline, GDP grew in real terms, particularly between 2011 and 2014. Monetized health damages as a share of total GDP have fallen from as high as 9.6% in 2008 to close to 7.7% in 2014 under baseline assumptions.

The reduction in annual damages between 2008 and 2014 have largely been driven by falling health damages attributable to point sources, which have dropped by close to $160 billion from 2008 to 2014, a decrease of 38%. Area sources comprise a larger share of total damages, in part because of their low release height and close proximity to population centers; these damages also declined slightly between 2008 and 2011 but have remain relatively flat. The decline in emissions and damages over this six year period is in line with a decades-long trend of reductions in observed PM$_{2.5}$ concentrations [43].

Despite a national trend of reduced health damages, benefits have not accrued uniformly across US counties. Figure 2 illustrates the change in per capita health damages incurred annually by each county from emissions levels in 2008 and 2014 (see SI section G for additional maps). In general, counties in the Northeast have benefited the most from reductions in damages between 2008 and 2014. However, 26% of US counties experienced an increase in health damages per person from 2008 to 2014, while 23% of counties showed an increase between 2011 and 2014. These counties are mostly concentrated in the South, Midwest, and the Pacific Northwest and in part coincide with increased area source emissions.

Although changes in population over this time period could affect per capita values, we find that absolute damages in many of these counties are still rising and that these changes in per capita damages are robust to changes in mortality rates, population, and changing marginal damages (see sensitivity analysis in SI section E). A sensitivity analysis using 2014 emissions with 2008 population levels and mortality rates is also consistent with our results. These results suggest that rising emissions are driving the increase in deaths from elevated PM$_{2.5}$ concentrations in these areas. Hotspots of increased damages tend to be driven by increased emissions from new industrial facilities, higher levels of oil and gas extraction, or increased light-duty transportation. For example, NO$_3$, VOCs, and primary PM$_{2.5}$ from oil and gas production activities rose by 75%, 80% and 180% nationally from 2008 to 2014, largely focused in the Marcellus region, North Dakota, and parts of the Midwest (see SI section G for a breakdown of changes to damages by sector).

It is important to note that any underlying changes to NEI are captured by the analysis presented in figure 2 and throughout the paper. For example, the NEI reports large increases in emissions from wildfires, prescribed burns, and agricultural burning in Florida and the Pacific Northwest between 2008 and 2014. In the case of Florida, this increase may be partly attributable to changes the EPA made in estimating emissions from agricultural burning over the period of this analysis. The results from figure 2 reflect such changes, and provide insight on trends and patterns over time within the NEI.

3.2. Inter-county and regional damage flows

Of the total health damages from emissions in the US, our modeling indicates that around 70% were related to emissions that were produced in a different county than where the damages occurred in each
Figure 1. Annual health damages from PM$_{2.5}$ exposure in the US fell from 2008 to 2011, and subsequently held constant through 2014, although the ratio of total damages to annual GDP continued to fall (a). In addition to a baseline estimate, a range of damages is shown based on upper and lower assumptions for VSL and concentration-response function (see SI section E for additional sensitivity analysis). The decline in damages is driven largely by falling emissions of direct PM$_{2.5}$ and its precursors over that time period (b). The fact that damages are steady between 2011 and 2014 even as emissions continue to fall is partly attributable to increasing marginal damage from pollution, and (c) illustrates the average marginal damage across all counties for medium stack heights. All dollar values shown in $2014.

Figure 2. Change in annual, per capita health damages from 2008 to 2014 by the location of the county where those health damages occur (in $2014 per person). See SI section G for additional maps of other time periods and of changes in absolute damages.

Figure 3 shows the regional attribution of PM$_{2.5}$-related mortality in the US (see SI section H for a description of these regions). Emissions within a region are typically responsible for the majority of the three years modeled. Further, in 2014 around 32% of annual damages occurred in a state different from the one that was the source of emissions, down slightly from 36% in 2008.
Table 1. Share of mortality [%] by EPA region from all sources of PM2.5 air pollution in 2008 (a) and 2014 (b). The region where the pollution causing the damage originated is listed by row, while the region where the damage is occurring is listed by column. The numbers in the matrix indicate the percent of annual deaths in a column region that are attributable to row region (with columns summing to 100%). Annual deaths caused by a region are summed by row, while annual deaths occurring in a region are summed by column; mortalities are shown to 2 significant figures. A comparable plot showing results for 2011 can be found in SI section I.

Figure 3. Share of mortality [%] by EPA region from all sources of PM2.5 air pollution in 2008 (a) and 2014 (b). The region where the pollution causing the damage originated is listed by row, while the region where the damage is occurring is listed by column. The numbers in the matrix indicate the percent of annual deaths in a column region that are attributable to row region (with columns summing to 100%). Annual deaths caused by a region are summed by row, while annual deaths occurring in a region are summed by column; mortalities are shown to 2 significant figures. A comparable plot showing results for 2011 can be found in SI section I.

Figure 4. Maps showing the ratio of exported to imported PM2.5 related health damages that result from inter-county emissions and their subsequent effect on PM2.5 concentrations. Ratios are shown by county for 2008 (a) and 2014 (b). Ratios < 1 indicate net importers, or counties that import more damages than they export, while ratios > 1 indicate net exporters.

Total damage incurred, as indicated by results on the diagonal. There is a relatively high degree of damage transfer between regions in the Eastern part of the country, although the share over damages incurred from transported emissions decreased from 2008 to 2014. New England is the largest importer; in 2008 just over half of its health damages were attributable to upwind emissions originating in the New York and Mid-Atlantic regions. However, by 2014 emissions within New England were responsible for a majority of the region’s damages (57%), with damages attributable to emissions in Mid-Atlantic states dropping from 18.1% to 12.8%. Generally, damages attributable to exports from the Midwest and Mid-Atlantic states declined the most, with the combined annual deaths from emissions in those regions falling by 12,000 from 2008 to 2014. Our findings on changes to transport at the regional level reflect a comparable pattern to previous work, which observed the share of PM2.5 damages attributable to out-of-state emissions decreasing from 49% to 38% from 2005 to 2018 [28].

The map in figure 4 shows the export/import ratio for PM2.5 health damages for each county in 2008 and 2014; export/import ratios greater than one indicate that an area is a net exporter, while ratios less than one indicate a net importer. Analysis of this metric at the state and metropolitan statistical area can be found in SI section F, while statistics on these values as well as maps of self-inflicted damages relative to imports and exports can be found in SI section I.

Most net importing counties are located in the Northeast, and large metropolitan areas also exhibit low export/import ratios, primarily because of large exposed populations and the fact that emissions in these areas tend to be dominated by vehicles, stationary non-point sources (restaurants, dry cleaners, etc.). In contrast, counties in the Great Plains, Mountain West, and Ohio river valley that have sparse...
populations tend to be net exporters of damages to downwind, more populous counties; this is particularly true for rural counties with large power plants or emitting facilities, which tend to have large export/import ratios. The counties showing the biggest upward shift in the export/import ratio are mostly concentrated in Appalachia and the Northeast; as emissions from coal-fired power plants fall in these counties, their export/import ratios fall. However, the opposite occurs in the surrounding downwind counties, which now import fewer emissions and as a result tend to experience increasing export/import ratios.

Despite the closure of large exporters, there is still disparity in the set of counties producing the most damages, with the top 14% of damage-causing counties causing 60% of exported damages and the top 1% of emitting counties responsible for almost 16% of exported damages in 2014 (see additional discussion in SI section J). Our modeling suggests that 60% of counties that were in non-attainment in 2014 could be in attainment were it not for pollution imported from out-of-state counties (see SI section K for details), a result that indicates the importance of continued interstate cooperation to mitigate pollution and achieve air quality standards.

3.3. Regression and environmental justice analysis
To better understand factors influencing the export/import ratios, we regress the log of the exported damages, imported damages, and the export/import ratio at the county level on a collection of covariates, including generation from coal power and natural gas plants, population, and whether a county is urban or rural. Figure 5 reports the fitted regression coefficients as percentage changes for each of the dependent variables; see SI section L for additional details on the covariates, the model formulation, and coefficient values.

The regression analysis demonstrates that the presence of a coal-fired power that generated three terawatt-hours (TWh) annually is associated with a 77% increase in the ratio of exported to imported damages (95% confidence intervals (CI): 71–83%), a change that is driven by an increase in exported damages. For reference, the largest coal generating county produced 30 TWh of electricity in a year, and 208 unique counties produced more than three TWh annually at least once over the period of the study. In contrast to coal, counties with 3 TWh of generation from natural gas plants show almost no difference in export/import ratios relative to counties without similar levels of generation from gas. Having meaningful generation from gas is associated with higher exported damages—albeit far less than coal—but also higher imported damages. This higher levels of imported damages may reflect the fact that the location of natural gas plants is weakly correlated with higher population levels (see SI section L).

We also explore issues of environmental justice and social equity by including the following in the regression: the percent of a county’s population under the federal poverty line, and the percent of the population that does not identify as primarily white, the latter which serves as a proxy for minority population. Figure 5 indicates the predicted percentage change in exported damages, imported damages, export/import ratio for counties with 10% and 20% population

![Figure 5](image-url)
below the poverty and 5% and 20% nonwhite population (the bottom and top quartiles of the data). A county with 10% of its population under the poverty line is associated with a 28% lower export/import ratio (95% CI: 24–32%) relative to a hypothetical baseline county with none of its population below the poverty line. In contrast, a county with 20% of its population under the poverty level is associated with 56% lower ratios (95% CI: 48–65%). This seems to be primarily driven by lower levels of exported damages, which may be reflective of fewer emissions due to lower economic activity and lower population levels.

To explore this further, we also look at the median health damages incurred or caused by county relative to its median income, shown in figure 6. The figure demonstrates that counties with lower median incomes tend to have higher levels of damages incurred and caused than the richest counties. In 2014, the poorest 20% of counties had median, per capita health damages of approximately $4500 per person, while the richest 20% of counties had damages 30% lower at $3100 per person. Thus, although poorer counties exhibit lower total export/import ratios relative to wealthier counties, the damages per person incurred in and caused by those counties tends to be higher.

The disparity by race in export/import ratio is somewhat less pronounced. Counties that are 5% nonwhite have 6% lower export/import ratios (95% CI: 4–8%) relative to a hypothetical county baseline county with no minority population, compared to 24% lower for counties that are 20% nonwhite (95% CI: 17–31%). Counties with higher non-white population tend to have both higher exported and imported damages, with imports growing more rising more quickly with non-white population. Higher exported damages are consistent with traditional environmental justice work that has found polluting facilities are more frequently located in areas with non-white populations [44–46], but the finding that these communities also have higher imported damages reflects the importance of considering the physical transport of air pollutants from other jurisdictions. When looking at median per capita health damages, we find a non-monotonic relationship, with the highest incurred damages in counties with the lowest and highest shares of non-white population. A similar pattern is evident in per capita damages caused, although the highest levels of damages are in counties with low non-white populations. This likely reflects the fact that large emitters like coal plants are often sited in rural areas, which are sparsely population tend to be whiter.

It is important to note that previous work has found that coarse spatial resolution—such as the county level which we use here—can underestimate disparities in PM$_{2.5}$ exposure, particularly by race. Despite this limitation, we find that counties with higher poverty levels and higher shares of
minority populations tend to be associated with lower export/import ratios and higher per capita damages caused and incurred. Although part of this effect is likely driven by the fact that vulnerable populations have higher baseline mortality rates, these findings are consistent with other research indicating that non-whites and individuals with lower socioeconomic status tend to have higher exposure to various components of PM$_{2.5}$ pollution, thus bearing a disproportionate share of the subsequent health burdens [47–50]. Median per capita damages tend to fall across the board from 2008 to 2014, but relative disparities by income and race persist. This finding is consistent with previous work showing that the most polluted areas historically tend to remain the most polluted even as absolute benefits accrue to all regions [43].

4. Discussion

Falling emissions from point sources over 2008 to 2014 have contributed substantially to the reduction in health damages from exposure to PM$_{2.5}$, with deaths falling by 23,000 annually. This dramatic decline is largely attributable to coal plants, many of which have closed for economic reasons or have begun to operate emissions control technology. In contrast, area sources have proved more persistent, remaining relatively flat from 2008 to 2014. This slowing decrease may be explained in part by increased economic activity toward the end of the Great Recession, as EPA estimates of emissions from construction and on-road vehicles are directly tied to economic indicators. Such increases attenuate health gains from falling point source emissions, particularly in more rural counties where drilling often occurs.

Declining emissions levels have been used by some to advocate for a diminished federal role in regulating air quality. Yet our results underscore the continued importance of inter-county, interstate, and regional flows of pollution and policies capable of reducing them. In 2014 imports accounted for over 90% of total annual health damages from PM$_{2.5}$ in nearly a third of US counties; for 90% of counties, 75% of damages are imported from elsewhere. These illustrate that emissions flows are the dominant source of health damages from PM$_{2.5}$ across most of the country.

Geographic variability in the relationship between damages from exported and imported emissions suggests the need for county-specific approaches to reducing PM$_{2.5}$ induced damages. For less-populated counties with high export/import ratios, concentrating on single point sources is likely to prove effective. In contrast, urban centers with large self-inflicted damages may benefit from pursuing emissions reductions within their own jurisdictions, including often hard-to-tackle, ground-level area sources. Interstate cooperation will be critical for major urban centers with large shares of imported damages, affirming the need for good neighbor policy.

Our analysis finds that counties with higher damages from imported pollution relative to exports tend to have higher levels of poverty and minority populations. This finding complements other environmental justice work by suggesting that attention should also be focused on understanding what populations are primarily affected by the transport of emissions and PM$_{2.5}$, and not simply proximity to emissions sources.

This analysis does not model interdependencies in the trade of economic goods and services associated with emissions, for which granular data is lacking, and future work should explore how to establish those linkages. Despite this obstacle, however, the concentration of decision-making and representation in local, county, and state governments makes this an important unit of analysis. The dichotomy between the interdependencies of health damages from PM$_{2.5}$ and the jurisdictional boundaries of local political systems implies the need for more integrated emissions planning that connects producers who emit with those that utilize those goods and services. Future work may also better account for uncertainty in pollution dispersion by modeling different meteorological conditions or incorporating results from an ensemble of air quality models.

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Author contributions

B.S., I.A., and N.M. conceived and scoped the project; N.M. developed the AP3 model; B.S. and N.M. used the model to conduct the analysis. B.S. interpreted the results and wrote the paper with input from all co-authors.
Competing interests

The authors declare no competing interests.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. Source code for AP3 is online at https://public.tepper.cmu.edu/nmuller/APModel.aspx, and portions of code and the data used for this work are available at https://github.com/bsergi/Inter-county-damages.

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