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Letter

Sociodemographic Disparities in Mercury Exposure from United States Coal-Fired Power Plants

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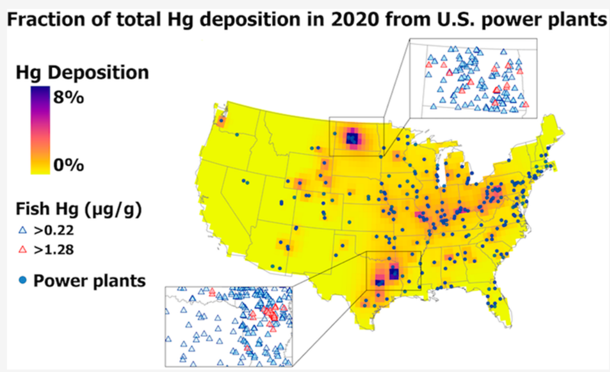

ABSTRACT: Hazardous air pollutants emitted by United States (U.S) coal-fired power plants have been controlled by the Mercury and Air Toxics Standards (MATS) since 2012. Sociodemographic disparities in traditional air pollutant exposures from U.S. power plants are known to occur but have not been evaluated for mercury (Hg), a neurotoxicant that bioaccumulates in food webs. Atmospheric Hg deposition from domestic power plants decreased by 91% across the contiguous U.S. from 6.4 Mg in 2010 to 0.55 Mg in 2020. Prior to MATS, populations living within 5 km of power plants (n = 507) included greater proportions of frequent fish consumers, individuals with low annual income and less than a high school education, and limited English-proficiency households compared to the US general population. These results reinforce a lack of distributional justice in plant siting found in prior work. Significantly greater proportions of low-income individuals lived within 5 km of active facilities in 2020 (n = 277) compared to plants that retired after 2010, suggesting that socioeconomic status may have played a role in retirement. Despite large deposition declines, an end-member scenario for remaining exposures from the largest active power plants for individuals consuming self-caught fish suggests they could still exceed the U.S. Environmental Protection Agency reference dose for methylmercury.

KEYWORDS: *Coal, Air Toxics, Power Plants, Mercury, Environmental Justice*

1. INTRODUCTION

Coal-fired power plants are well-established sources of criteria air pollutants that cause degraded air quality,[1] acid rain,[2] and premature mortality.[3] Coal combustion also releases more than 200 hazardous air pollutants (HAP) including arsenic, acid gases, and mercury (Hg).[4] In the environment, Hg is converted into methylmercury, which is the only form of Hg that biomagnifies in food webs. Methylmercury exposure is particularly harmful for the developing brain and can lead to neurodevelopmental deficits in children that persist over a lifetime.[5,6] Adult methylmercury exposures have been associated with increased cardiovascular disease risk.[7−9] Siting of United States (U.S.) power plants has been linked to disparities in exposures to traditional air pollutants such as fine particulate matter ($PM_{2.5}$) and ozone.[10,11] One study found that exposure−response relationships differed among racial/ethnic groups, leading to an underestimate of the health benefits to older Black Americans from improvements in air quality associated with the Mercury and Air Toxics Standards (MATS).[12] Another study noted that neighborhoods with the highest perceived investment risks, designated as "red-lined" areas with high proportions of people of color and foreign-born residents, also had the greatest numbers of fossil fuel power plants within 5 km.[13] Here, we examine at the national scale whether sociodemographic disparities in Hg exposures from U.S. power plants have also occurred.

Hg is a naturally occurring heavy metal that is enriched in coal relative to other fossil fuels. The worldwide average Hg content of coal is 0.10 ± 0.01 $\mu g\ g^{-1}$ (typical range ∼0.01−1.0 $\mu g\ g^{-1}$)[14] compared to negligible concentrations in processed natural gas.[15] In 2005, U.S. coal-fired power plants were the largest domestic source of Hg emissions and accounted for 50% of the national total.[16] Upon combustion, Hg in coal is released to the atmosphere in two main chemical forms: elemental mercury (Hg^0) and divalent mercury (Hg^{II}). Hg^{II} is highly water soluble and deposits locally following emission. By contrast, Hg^0 is stable in the atmosphere with a lifetime of months enabling hemispheric to global transport.[17] The MATS rule was promulgated under Section 112 of the U.S. Clean Air Act as a technology-based standard rather than a cap-and-trade-based rule because of the potential for enhanced Hg^{II}

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deposition and associated risks to the populations surrounding coal-fired utilities.[18] Past research suggests controlling Hg emissions will reduce fish methylmercury levels proportionally to changes in Hg inputs at harvesting locations, thereby reducing human exposures.[19−21]

Fish and shellfish are the main vectors of human exposure to methylmercury in the U.S. because Hg concentrations in higher trophic level organisms (such as piscivorous fish) are typically 10^{6-7} higher than those in water due to biomagnification.[22] Statistically representative cross-sectional survey data from the U.S. population (National Health and Nutrition Examination Survey [NHANES]) showed highest blood Hg concentrations among individuals identifying as Asian, Pacific and Caribbean Islander, Native American, Alaska Native, multiracial, and unknown race due to their frequent fish consumption.[22−24] In a U.S. national survey of individuals who consumed three or more fish meals per week, participants with low income (<$20,000 USD annual income) and low education (<high school) had statistically significantly higher consumption rates.[25]

The main objectives of this work are to (1) test whether highly exposed or marginalized groups disproportionately reside near U.S. power plants relative to the general population, (2) examine whether these subpopulations benefited equally from changes in atmospheric Hg deposition before and after MATS, and (3) construct an end-member scenario for the highest potential Hg exposures from U.S. power plant emissions in 2020. Results of this analysis improve understanding of sociodemographic disparities in exposures to Hg emissions from coal-fired power plants. Multiple legal challenges have occurred since implementation of MATS and the rule was reaffirmed by the Biden administration in 2023.[18] The present study will help to inform revisions to the risk and technology review associated with this rule that examines residual exposures for the most vulnerable individuals.

2. METHODS

2.1. Changes in Hg Emissions and Deposition from U.S. Power Plants. We compiled data on the locations, control technology, and Hg emissions for all U.S. coal- and oil-fired power plants in 2010 and 2020, which represent the periods before and after MATS was promulgated in 2011. Locations and emissions data were obtained from the MATS Information Collection Request (ICR) for 2010 and from reporting data compiled by the U.S. Environmental Protection Agency (U.S. EPA) for 2020.[26] For each plant operating in 2010 (n = 507), we characterized 2020 operating status as *fully retired* (n = 230) if all plant boilers were retired, *partially retired* (n = 62) if some but not all boilers were retired, and *fully operational* (n = 215) if all boilers were still used. Since only coal- and oil-fired boilers are subject to MATS, our retirement criteria may include instances where boilers were converted to burn natural gas. Conversion to natural gas is not expected to produce significant emissions since Hg is typically removed from raw gas during recovery and processing,[27] and oil-combustion accounted for <1% of the total Hg emissions from power plants in 2010 (Table S1).[26] Hereon, we refer to coal- and oil-fired boilers as "power plants".

We simulated atmospheric Hg deposition from U.S. power plants in 2010 and 2020 using a nested high-resolution (0.5° × 0.625° horizontal resolution) version of the GEOS-Chem atmospheric chemical transport model (CTM). The model has 47 vertical layers extending from the surface into the stratosphere. The nested model domain covered North America (40°−140° W; 10°−70° N) with boundary inputs generated from a global simulation with 4° × 5° horizontal resolution.[28] We conducted four-year simulations forced by emissions from U.S. power plants and all global sources in 2010 and 2020 using assimilated meteorological data from satellite observations (Modern-Era Retrospective analysis for Research and Applications, Version 2: MERRA-2)[29] for the years 2016−2020. We held the meteorological years constant for all simulations to ensure that differences in deposition were attributable to changes in anthropogenic Hg emissions. The first two years were used for model spin-up and the final two years for analysis. The standard GEOS-Chem Hg simulation is described elsewhere and has been evaluated using available atmospheric observations.[28] For simulations that considered total Hg deposition from all sources, we used the standard GEOS-Chem simulation and global Hg emissions from Streets et al.[30,31]

2.2. Characterization of Potentially Vulnerable Populations. We considered exposures to Hg emitted from power plants for individuals who were already highly exposed or potentially marginalized groups. Past cycles of NHANES show individuals who frequently consume fish had the highest blood Hg concentrations and self-identified in the following racial/ethnic categories: Asian, Pacific and Caribbean Islander, Native American, Alaska Native, multiracial, and unknown race.[22−24] We matched these categories with their closest equivalents in the U.S. Census Bureau's American Community Survey (ACS): Asian, Native Hawaiian and Other Pacific Islander, American Indian and Alaska Native, two or more races (multiracial), or some other race alone. We did not include individuals identifying as "Caribbean Islander" because this subgroup was not identified by either race or ethnicity in the ACS. Available data suggest most Caribbean Islander immigrants are colocated with other high-frequency fish consumer populations in East Coast cities, meaning their omission is unlikely to substantially affect our results.[32]

We included the sociodemographic variables: "annual household income of less than $20,000" and "less than high school education level achieved for adults age 25 and older" because a national survey of high-frequency fish consumers revealed these individuals had statistically greater levels of fish consumption compared to other groups.[25] We also included a more generalized description of poverty (income to poverty ratio less than 200% of the federal poverty line [PIR < 2]) and limited English-speaking households. Households with lower income and limited English proficiency may be marginalized and exhibit greater vulnerability to environmental toxicant exposures compared to other groups.[1−3]

2.3. Sociodemographic Analysis of Residents Surrounding Power Plants. To investigate the sociodemographic characteristics of populations residing near U.S. power plants, we downloaded data and polygons on U.S. census blocks groups for 2006−2010 (n = 217,740) and 2016−2020 (n = 239,780) from the National Historical Geographic Information System.[33] We characterized the residential populations surrounding power plants that were operational in 2010 (n = 507). Specifically, we identified overlapping census block groups in a 5 km circular buffer around power plants (13,329 census block groups). We chose the 5 km distance for consistency with prior work[13] and based on variability in census block group sizes across the country. We compared the sociodemographic attributes of residents living

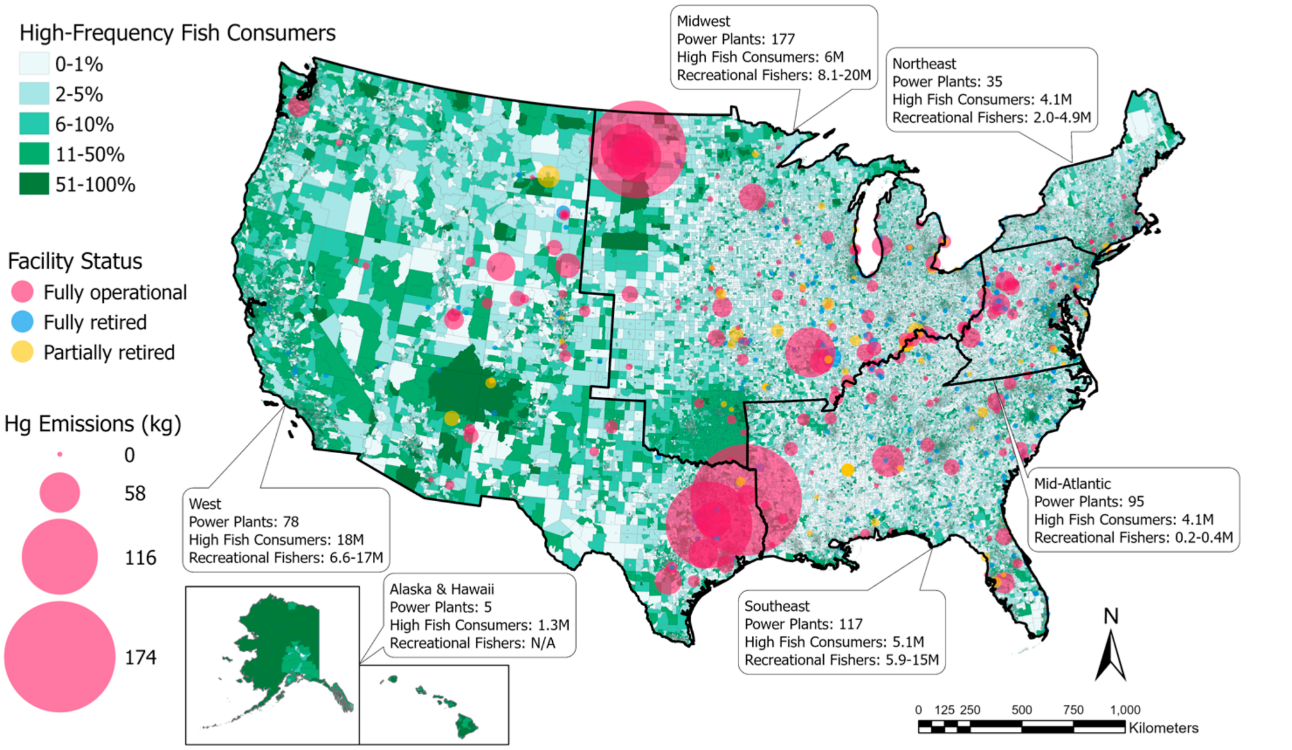

Figure 1. Locations of U.S. power plants[26] in 2010 and frequent fish consumers likely to have elevated mercury exposures. Power plants are shown by active (pink), retired (blue), and partially retired (yellow) status in 2020 with circle size indicating emissions magnitude. Intensity of green color indicates proportion of each census block group[33] characterized as high-frequency fish consumers based on racial/ethnic categories that report elevated consumption[22−24] (Asian, Native Hawaiian and Pacific Islander, American Indian and Alaska Native, multiracial, or other race). The most saturated colors indicate where >50% of the population are considered high-frequency fish consumers, while the lightest colors indicate where this demographic represents less than 1% of the population. Numbers of recreational anglers in each region are displayed in callouts based on a 2001 survey.[40]

within and outside the buffer regions and conducted a sensitivity analysis by varying the buffer radius between 1 and 100 km (Text S1). Significance was established if 95% confidence intervals between the two groups were non-overlapping. We chose this approach because large differences in the distributions of the two sample populations made it difficult to satisfy the assumptions of standard parametric/nonparametric difference tests.

We investigated whether the sociodemographic characteristics of residents within 5 km of power plants that remained active in 2020 differed from those near facilities that had retired since 2010. Facilities were considered active if any of their boilers were operational in 2020 (fully operational and partially retired) or retired if all boilers had been retired (fully retired). A Wilcoxon rank-sum test was used to determine if significant sociodemographic differences existed among populations of residents next to active and retired power plants, where significance was determined as $p < 0.05$. We also conducted a spatial clustering analysis of Hg deposition and each sociodemographic variable (Text S2). All spatial and statistical analyses were conducted using ArcGIS Pro 3.0.1 and *sf*, *spatstat*, *raster*, and *spdep* packages in R version 4.2.1.[34−37]

2.4. Residual Risks of Hg Exposure from U.S. Power Plants in 2020. We constructed an end-member scenario to identify if remaining Hg exposures attributable to U.S. power plants in 2020 among the most highly exposed individuals are likely to exceed the U.S. EPA reference dose (RfD) for methylmercury (0.1 μg kg^{-1} body weight per day).[38] Past research suggests controlling atmospheric Hg emissions will reduce fish methylmercury levels proportionally to the changes in Hg inputs at harvesting locations.[19−21] We therefore focused this analysis on anglers who consume 100% self-caught fish. We first identified regions across the contiguous U.S. with the maximum remaining fraction of total atmospheric Hg deposition from U.S. power plants (f_{PP}, %) using the GEOS-Chem atmospheric modeling data.[28] We compiled data on the 90th percentile to maximum fish consumption rates (Fish Intake = 78−336 g day^{-1}) for anglers who reported consuming only self-caught fish in a national survey of high-frequency fish consumers.[25] We assumed an average body weight (bw, kg) between 60 and 80 kg and back-calculated Hg concentrations in recreational fish species (Fish$_{Hg}$, μg g^{-1}) that would push consumers above the RfD from power plant Hg sources alone (i.e., $\mathrm{Fish_{Hg}} > \frac{\frac{\mathrm{RfD}}{f_{PP}} \times \mathrm{bw}}{\mathrm{Fish\ Intake}}$). More than 95% of the total Hg in piscivorous fish species is methylmercury,[39] so we assume equivalence between Hg species. We compared measured fish Hg concentrations from regions surrounding power plants with the highest contributions to overall Hg deposition in 2020 to the back-calculated Fish$_{Hg}$ from our bounding analysis to determine if power plant emissions alone are likely to still pose a plausible risk to the most highly exposed fish consumers.

3. RESULTS AND DISCUSSION

3.1. Locations of Power Plants and Frequent Fish Consumers. Emissions of Hg from U.S. power plants declined from 24.3 Mg in 2010 to 2.5 Mg in 2020 following full implementation of MATS, a decrease of 90%.[26] In 2010, there

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Table 1. Sociodemographic Differences in Populations Surrounding Power Plants

	Frequent fish consumers[a]	PIR < 2[b]	Income < $20,000 USD[c]	< High school[d]	Limited English speaking[e]
Fraction of the population in 2010:[f,g]					
<5 km from power plants	9.5% ± 0.17%	36% ± 0.45%	21% ± 0.86%	18% ± 0.67%	6.9% ± 0.87%
# individuals (millions)	1.5 ± 0.028	5.8 ± 0.075	3.4 ± 0.14	2.9 ± 0.11	1.1 ± 0.14
>5 km from power plants	8.0% ± 0.038%	32% ± 0.13%	17% ± 0.17%	15% ± 0.26%	5.2% ± 0.17%
# individuals (millions)	23 ± 0.11	92 ± 0.37	50 ± 0.48	44 ± 0.74	15 ± 0.49
Median fraction of the population in 2020 less than 5 km from:					
Active power plants	6.63%	36.3%	16.7%	10.9%	1.73%
Retired power plants	12.7%	31.7%	16.3%	11.8%	7.78%
p-value	0.35	0.02[h]	0.03[h]	0.02[h]	0.02[h]

[a]Frequent fish consumers = racial populations with significantly elevated mercury exposures in the U.S. Census matching National Health and Nutrition Examination Survey (NHANES) data, specifically individuals identifying as Asian, Hawaiian and Pacific Islander, American Indian and Alaska Native, multiracial, or other race. [b]Individuals with an income to poverty ratio (PIR) less than 200% of the federal poverty line. [c]Households with annual income of less than $20,000 USD. [d]Population 25 years or older with less than high school education (completing less than regular high school diploma). [e]Limited English-speaking households. [f]Fraction of the population in 2010 represent central estimate and 95% margin of error values. [g]Based on all power plants with at least one active boiler in 2010 and U.S. Census data for 2006−2010. [h]Denotes significant difference $p < 0.05$ based on the Wilcoxon rank-sum test for 2016−2020 census block groups falling within 5 km of active plants in 2020 compared to those that retired since 2010. Note that this test determines whether two populations are significantly different rather than differences in population central tendency values.

were 507 power plants (Figure 1). By 2020, 230 plants were fully retired, 62 had retired some of their boilers, and 215 remained fully operational (Figure 1). Regionally, the largest fraction of plant retirements between 2010 and 2020 occurred in the Northeast (50%). Most active plants in 2020 emitted <5 kg of Hg to the atmosphere per year, but the highest emitting plants in North Dakota and Texas emitted >100 kg of Hg and combusted predominantly lignite coal (Figure 1).

We first qualitatively examined coincident location of power plants, recreational fishers, and high-frequency fish consumers across the contiguous U.S. (Figure 1). The greatest numbers of all three are in the Midwest. Individuals with elevated blood Hg concentrations who are frequent fish consumers in national survey data[22−24] (identifying as Asian, Native Hawaiian and Pacific Islander, American Indian and Alaska Native, multiracial, or other race) make up 12% of the U.S. population (green shading, Figure 1). A 2001 survey suggested there are ∼34 million recreational anglers in the U.S. and that 16% of adults aged 16+ participated in fishing activities.[40]

3.2. Sociodemographic Differences in Populations Residing Next to Power Plants. Proportions of all the highly exposed or marginalized populations considered in this work residing near U.S. power plants in 2010 were significantly higher than their mean proportions in the U.S. general population (Table 1). Greatest differences were observed for the two sociodemographic attributes related to income, where ∼36% of residents within 5 km of a power plant had a PIR < 2 and ∼21% had an annual income of < $20,000 USD compared to 32% and 18%, respectively, in the U.S. general population. Sensitivity analyses varying the 5 km buffer radius revealed differences observed for low income and poverty were significant for populations living up to 15 km away from power plants (Figure S1). In combination with earlier work showing greater abundance of power plants within 5 km of red-lined neighborhoods,[13] this work adds to the evidence for a lack of distributional justice in plant siting.

Areas with lower income are less likely to have a retired power plant. Approximately 5.8 million people with a PIR < 2 lived within 5 km of active power plants in 2020 (Table 1). The median proportion of individuals within 5 km of active power plants in 2020 that had PIR < 2 was 36.3%, compared to 31.7% for those that had retired since 2010. The median proportion of households with less than $20,000 USD annual income was 16.7% near active plants, compared to 16.4% near retired ones. Both factors' population distributions were statistically significantly different ($p < 0.05$) between active and retired plants (Wilcoxon rank sum test; Table 1). Sensitivity analyses varying the 5 km buffer radius showed results remained statistically significant up to 15 km away from power plants (Figure S2).

3.3. Spatial Patterns in Hg Deposition Reductions from Power Plants. Atmospheric Hg deposition to the contiguous U.S. from domestic power plants decreased from 6.4 Mg in 2010 to 0.55 Mg in 2020, a total change of 91% (Figure 2). Highest reductions in Hg deposition from U.S. power plants occurred throughout the Northeast and Southeast (Figure 2). We found spatial overlaps in the clustering of regions with higher than average reductions in Hg deposition and higher than average proportions of individuals earning < $20,000 USD income and < high school education in the U.S. southeast (Figure S3).

Lowest reductions in Hg deposition from U.S. power plants occurred in parts of North Dakota, Texas, and Nevada (Figure 2). We find clustering of these regions with lower than average reductions in deposition that overlap regions with higher than average numbers of high-frequency fish consumers, especially in North and South Dakota, and parts of Montana (Figure S3). The Dakotas have a high proportion of American Indians, who frequently consume fish, and many recreational fisheries are in this area.

3.4. Plausible Hg Exposure Risks from Highest Emitting U.S. Power Plants in 2020. Atmospheric Hg modeling indicated that the maximum fraction of local atmospheric Hg deposition attributable to U.S. power plants in 2020, after the MATS rule was fully implemented, was 8% in North Dakota followed by Texas (Figure S4). The total Hg concentrations in fish that would result in power plant-attributable Hg deposition alone exceeding the RfD for methylmercury[38] (see Methods) range from 0.22 to 1.28 μg g^{-1} wet weight. The range in fish concentrations reflects variability in body weights between 60 and 80 kg to capture different genders and ethnicities, as well as the 90th percentile to maximum local fish consumption frequencies reported in a national survey of high-frequency fish consumers.[25]

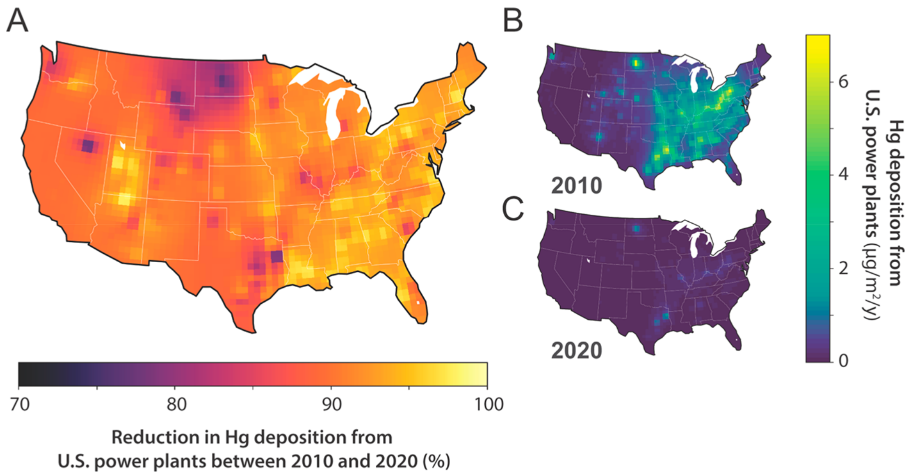

Figure 2. Modeled changes in atmospheric Hg deposition to the contiguous U.S. between 2010 and 2020 due to declines in Hg emissions from U.S. power plants. Panel (A) shows the percent reduction in Hg deposition attributable to shifts in emissions from U.S. power plants. Panels (B) and (C) show the absolute magnitudes of Hg deposition attributable to U.S. power plants in 2010 and 2020.

To evaluate if such exposures could plausibly occur, we examined measured Hg concentrations from prior fish Hg data synthesis efforts.[41,42] We focused on species commonly consumed by recreational anglers (trout, bass, salmon, pike, crappie, catfish, perch, walleye, sunfish) in North Dakota and the South-Central states (Texas, Louisiana, Oklahoma, Arkansas).[25] We found 64% (n = 2700) of North Dakota fish samples were above the estimated lower bound of 0.22 $\mu g\ g^{-1}$ for power plant attributable Hg exposures to exceed the RfD, and 3% (n = 114) exceeded the upper bound of 1.28 $\mu g\ g^{-1}$ (Figure S5, Table S1). For the South-Central states, 54% (n = 1134) of fish samples exceeded the lower bound and 5% (n = 106) exceeded the upper bound. This analysis suggests that exposures exceeding the U.S. EPA RfD for methylmercury are still possible for the most highly exposed individuals residing next to the largest remaining power plants in 2020. Despite large (90%) reductions in U.S. power plant emissions between 2010 and 2020, residual risks associated with methylmercury exposures from U.S. power plants are still plausible for the largest emitters in North Dakota and Texas. Extensive lignite coal combustion occurs in these regions, which requires more fuel per unit of energy than bituminous coal.[43] The U.S. EPA has proposed to further strengthen the MATS rule by more stringently regulating lignite coal sources.[44] This study suggests such actions would eliminate the last two remaining domestic mercury deposition hotspots attributable to U.S. coal fired power plants.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.3c00216.

> Mercury emissions by fuel type (Table S1), supplemental methods on sociodemographic analysis of residents surrounding power plants (Text S1), spatial clustering method (Text S2), sensitivity analysis to buffer radius for residents living between 1 and 100 km from U.S. power plants in 2010 (Figure S1) and 2020 (Figure S2), spatial clustering of Hg deposition reductions (Figure S3), modeled fraction of total atmospheric Hg deposition attributable to U.S. power plants in 2020 (Figure S4), and measured Hg concentrations for commonly consumed recreational fish species (Figure S5 and Table S2) (PDF)
>
> Locations and summary data (XLSX)
>
> Supporting code can be downloaded from https://github.com/SunderlandLab/sociodemographic_hg. Supporting data can be downloaded from https://doi.org/10.7910/DVN/9X5GEH

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Notes

The authors declare no competing financial interest.

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