Pollution inequality 50 years after the Clean Air Act: the need for hyperlocal data and action

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Keywords: air pollution 'hot spot', hyperlocal scale, data-driven sensor networks, clean air policy, environmental justice

Abstract
Effective solutions require integration of improved data, technology innovations, community engagement, and environmental justice.

1. Introduction

Fifty years ago the Clean Air Act amendments of 1970 were the first major US legislation that authorized regulation of air pollutants, creating National Ambient Air Quality Standards (NAAQSs) to protect public health and the environment. While US air quality has improved, with average PM\(_{2.5}\) concentrations in 2016 at a third of 1981 levels [1], air pollution remains a major health risk in the US and globally. Over 150 million people still live in areas exceeding NAAQSs [2], leading to \(\sim 200,000\) deaths yr\(^{-1}\) from ambient PM\(_{2.5}\) alone [3]. Moreover, air pollution impacts are still uneven with persistent racial/ethnic disparities in pollution exposure caused by different factors and mechanisms [4]; the most polluted US communities of 50 years ago still so today [1]. Air pollution ‘hot spots’ result in disproportionate exposure at hyperlocal scales (i.e. home, building, street, neighborhood) within cities, particularly in disadvantaged communities [5–7]. We currently lack the high resolution understanding of air quality necessary to design effective policy and mitigation strategies for affected communities. This paper provides insights into the drivers, historic perspectives, and challenges of hyperlocal air pollution in the US at the 50 year milestone of the CAA amendments of 1970. We make actionable recommendations toward socio-technical solutions that support achieving environmental justice for marginalized communities.

2. Drivers and historic influence

Urban air pollution, characterized by high levels of criteria pollutants (e.g. ozone (O\(_3\)), fine particulate matter (PM\(_{2.5}\)), and air toxics, is driven by emissions from vehicles, buildings, power plants, and industrial operations. Concentrations of environmental harm are inherently the product of relationships between distinct places, including industrial zones, affluent suburbs, working-class suburbs, and downtown, all of which are racialized [8]. These racialized systems shield some (affluent white communities) from environmental harm, while other communities bear disproportionate risks. Urban planning decisions locating infrastructure affect the geographical distribution of air pollution, which, in part, explains exposure disparities. Major urban highways, built in the 1950s–60s, still affect nearby communities. Warehouses operations and hazardous waste facilities, with large volumes of diesel truck traffic, have been disproportionately located in Black and Brown communities [9, 10]. Despite urban deindustrialization, over the past several decades, the effects of manufacturing history and its legacy of industrial air pollution remain significant in many urban areas [11].
Current and past housing policies, exclusionary zoning, and racial capitalism have reinforced segregation, making it harder for residents to move to areas with better air quality [12]. The result is unequal exposure to pollutants and significant differences in health risks. For example, Black and Latino/a/x communities bear an ‘air pollution burden’ of 60% more exposure than they generate by their consumption, while white communities experience 20% less than what is caused by their consumption [5–7]. The ongoing COVID-19 pandemic has reinforced links between air pollution and health and made systemic, racialized health inequalities more apparent in the US [13, 14]. Addressing environmental justice issues requires an understanding of not only historical influences but also hyperlocal air pollution conditions at the community level, which are often neglected in current monitoring networks and decision-making processes [15].

3. Challenges and opportunities

Resolving air pollution hot spots is scientifically challenging due to the influence of multiple pollutants, their inherent linkages, uncertainties in pollution sources (e.g. local vs. upwind, primary vs. secondary, traditional vs. new mobility services), as well as variable conditions (e.g. outdoor vs. indoor, summer vs. winter, urbanization, land use, climate change, weather extremes). Current state-of-the-science fine-scale (∼1 km) estimates of air pollution combine satellite data, surface measurements, coarser resolution modeling, and statistical methods [16, 17]. Land use regression models incorporate surface monitoring data, land-cover/use data, and, sometimes, satellite-data to estimate air pollutant concentrations at a high resolution (≤1 km) [18]. However, such models are not validated at fine scales, cannot resolve hot spots at hyperlocal scales or provide information at higher temporal resolution. For instance, PM concentrations are correlated with traffic volume and velocity, type of vehicles, size and aspect ratio of urban canyons, and weather conditions [19], resulting in distinct microenvironments with heterogeneity in air pollution exposure at 30 m scale [20]. This leaves the distribution and characteristics of hot spots uncertain due to a lack of fine-scale emission, concentration, and exposure data [21].

Trends in sensor technology, spatial data collection and retrieval, and analytics are converging to enable the production of hyperlocal air pollution data. GPS data from cellphones and vehicles are revealing with unprecedented detail individual and community mobility patterns [22]. High-quality monitoring using mobile sensors is increasing [20] to the point where data are being generated for every street, providing unprecedented spatial detail [23]. Autonomous vehicles can systematize data gathering, while drones enable air quality sensing in 3D, in locations that have hitherto been inaccessible. The launch of geostationary satellites such as the tropospheric emissions: monitoring of pollution over North America will provide near-real-time high spatio-temporal resolution data (e.g. O3, NO2, PM2.5), to track hourly daytime air pollution at micro urban scales (2–4.5 km) [24], which will significantly improve air quality predictions. Some cities are also building digital twin models to track building energy use and traffic, which can be extrapolated to emissions.

Current monitoring, e.g. the EPA Federal Reference Method for PM, relies on high-accuracy yet costly instrumentation, with most cities having at most a few monitoring stations. Optically-based ‘low cost’ sensors show promise, if combined with methodologies to account for relatively high uncertainties and biases (up to 25 µg m⁻³) compared to typical PM levels in US cities (∼15 µg m⁻³) [25]. As affordable sensors became available it will be necessary to optimize the development of cost-effective sensor networks and cyberinfrastructure that provide data with the necessary spatiotemporal resolution to understand air quality heterogeneity in cities and to design mitigation and response policies. However, given algorithmic racism and discriminatory surveillance technologies, environmental monitoring systems need to be designed to be anti-racist by analyzing data for bias and protecting data privacy as well as making the data accessible for those most at risk. Data systems need to enable marginalized communities to shape decision making, as called for in the recently introduced ‘Environmental Justice Mapping and Data Collection Act’ [26]. Additionally, data needs to move beyond documenting inequitable exposures to illustrating the social and technical dynamics producing inequitable risk such as suburban commuter congestion impacting urban areas.

These technical challenges are layered on the complexities of understanding exposure implications for populations—i.e. determining how to convert air pollution data into health impacts and then into decisions that bring material improvement for those most at risk. Quantifying risk exposure is difficult because of interactions between multiple different pollutants experienced simultaneously or across different environments (commute, workspace, home) along with differential individual sensitivity to the same exposure. Ignoring human mobility may lead to inaccurate assessment of individual exposure [27].

The location and characteristics of hyperlocal air pollution hot spots may also change over time with new transportation and energy generation regimes, which may alter policy response options. For instance, rideshare services have boomed in the past decade, changing the landscape of urban transportation; the relationship of rideshare to congestion and air quality effects is not well understood, and there are
indications that this new mode may decrease public transit ridership [28]. Increasing the number of electric vehicles and integration with transit services as last-mile connections could substantially mitigate these issues as the share of solar and wind in electricity generation increases; however, these new services are already less available to disadvantaged communities. While the evolution of transportation systems is likely to change hyperlocal conditions within cities, macroscopic changes in energy systems will continue to modify regional background conditions that also influence local conditions.

4. Science and policy recommendations

The concurrent trends of growing urbanization, climate change, and continuing disparities highlight the need for convergent research that bridges social, political, biological, and physical sciences. Air quality is determined by a combination of public policy, land-use decisions, social norms, inequality, and economic activities, logically, effective mitigation strategies require understanding of the historical, socio-technical, economic and policy factors leading to environmental injustice [8, 29, 30].

We believe that the following actions can address current limitations to improve air quality and equity:

- Increase investment from federal, state, and municipal agencies for hyperlocal air quality monitoring and modeling in cities, focusing on disadvantaged communities, to better characterize air pollution hot spots (locations and sources).
- Foster innovation in estimating exposures by including proxy sensors, new data-driven methods, and physics-based models of the built environment to better understand the linked systems of indoor and outdoor air quality in homes, workplaces, schools, and transit.
- Engage community groups and citizen scientists to build and manage neighborhood-based surveillance networks to better monitor local air quality and report pollution hot spots and events.
- Extend and improve environmental justice analyses through detailed mapping of air pollution levels, working toward an understanding of the drivers of environmental harms.
- Enable more effective air pollution and environmental injustice interventions by incorporating hyperlocal pollution data into policy frameworks.

Most importantly, advancements in scientific and policy understanding must be paired with a historical understanding of the policies, events, beliefs, and trends that generate and maintain racialized and gendered environmental health disparities. Only in this way can we co-produce solutions that will work in specific community contexts.

Data availability statement

No new data were created or analyzed in this study.

Acknowledgments

This work is supported in part by the TIRE2 Research Development Funds, Northeastern University, the U.S. Environmental Protection Agency to Yale University through the SEARCH (Solutions for Energy, Air, Climate, and Health) Center under Assistance Agreement No. RD835871, and the National Oceanic and Atmospheric Administration (NOAA) Atmospheric Chemistry Carbon Cycle and Climate (AC4) Award Number: NA20OAR4310293. It has not been formally reviewed by EPA. The views expressed in this document are solely those of the SEARCH Center and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication.

Conflict of interest

The authors declare that there are no conflicts of interest.

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References

[1] Colmer J, Hardman I, Shimshack J and Voorheis J 2020 Disparities in PM2.5 air pollution in the United States Science 369 575–8
[2] American Lung Association (ALA) 2020 State of the Air 2020 (available at: www.stateoftheair.org/key-findings/
[3] Bowe B, Xie Y, Yan Y and Al-Aly Z 2019 Burden of cause-specific mortality associated with PM2.5 air pollution in the United States JAMA Network Open 2 e1915834
[4] Kravitz-Wirtz N, Crowder K, Hajat A and Sassi V 2016 The long-term dynamics of racial/ethnic inequality in neighborhood air pollution exposure, 1990–2009 Du Bois Rev.: Soc. Sci. Res. Race 13 237–59
[5] Tessum C W et al 2019 Inequity in consumption of goods and services adds to racial-ethnic disparities in air pollution exposure Proc. Natl Acad. Sci. USA 116 6001–6
[6] Son J-Y, Lane K J, Miranda M L and Bell M L 2020 Health disparities attributable to air pollutant exposure in North Carolina: influence of residential environmental and social factors Health Place 62 102287
[7] Wu J, Watkins D, Williams J, Bhagat S V, Kumar H and Gentileman J 2020 Who gets to breathe clean air in New Delhi? (available at: www.nytimes.com/interactive/2020/12/17/world/asia/india-pollution-inequality.html?smid=em-share)
[8] Pulido L 2000 Rethinking environmental racism: white privilege and urban development in southern California Ann. Am. Assoc. Geogr. 90 12–40
[9] Mohai P and Saha R 2015 Which came first, people or pollution? Assessing the disparate sited and post-siting demographic change hypotheses of environmental injustice Environ. Res. Lett. 10 115008
[10] Yuan Q 2018 Mega freight generators in my backyard: a longitudinal study of environmental justice in warehousing location Land Use Policy 76 130–43
[11] Smiley K T 2020 Metropolitan manufacturing decline and environmental inequalities in industrial air pollution in the united states Sociological Inquiry (26 October) (https://doi.org/10.1111/seoin.12396)
[12] Rothstein R 2017 The Color of Law: A Forgotten History of How Our Government Segregated America (New York: Liveright Publishing)
[13] Conticini E, Frediani B and Caro D 2020 Can atmospheric pollution be considered a co-factor in extremely high level of SARS-CoV-2 lethality in Northern Italy? Environ. Pollut. 261 114465
[14] Wu X, Nethery R C, Sabath B M, Braun D and Dominici F 2020 Exposure to air pollution and COVID-19 mortality in the United States: a nationwide cross-sectional study medRxiv (https://doi.org/10.1101/2020.04.05.20054502)
[15] Coursesen D 2021 Environmental justice requires adequate air quality monitoring system (available at: https://news.bloomberglaw.com/environment-and-energy/environmental-justice-requires-adequate-air-quality-monitoring-system) (9 March)
[16] Goldberg D L, Gupta P, Wang K, Jena C, Zhang Y, Lu Z and Streets D G 2019 Using gap-filled MAIAC AOD and WRF-Chem to estimate daily PM2.5 concentrations at 1 km resolution in the Eastern United States Atmos. Environ. 199 443–52
[17] Meng J, Li C, Martin R V, Van Donkelaar A, Hystad P and Brauer M 2019 Estimated long-term (1981–2016) concentrations of ambient fine particulate matter across North America from chemical transport modeling, satellite remote sensing, and ground-based measurements Environ. Sci. Tech. 53 5071–9
[18] Wang Y Z, Bechle M J, Kim S-Y, Adams P J, Pandis S N, Pope A III, Robinson A L, Sheppard L, Szpiro A A and Marshall J D 2020 Spatial decomposition analysis of NO2 and PM2.5 air pollution in the United States Atmos. Environ. 241 117470
[19] Yang H-Y, Chen T-H, Lin -Y-Y, Buccolieri R, Mattsson M, Zhang M, Hung J and Wang Q 2020 Integrated impacts of tree planting and street aspect ratios on CO dispersion and personal exposure in full-scale street canyons Build. Environ. 169 106529
[20] Apet J S, Messier K P, Gani S, Brauer M, Kir Christina T W, Lund M M, Marshall J D, Portier C J, Vermeulen R C H and Hamburg S P 2017 High-resolution air pollution mapping with Google Street view cars: exploiting big data Environ. Sci. Technol. 51 6999–7008
[21] Gately K, Hutyra L R, Peterson S and Wing I S 2017 Urban emissions hotspots: quantifying vehicle congestion and air pollution using mobile phone GPS data Environ. Pollut. 229 496–504
[22] Wangn Q, Phillips N E, Small M L and Sampson R J 2018 Urban mobility and neighborhood isolation in America’s 50 largest cities Proc. Natl Acad. Sci. USA 115 7735–40
[23] Tang M and Niemeier D A 2021 Using big data techniques to better understand high-resolution cumulative exposure assessment of traffic-related air pollution ACS ES&T Eng. 1 436–45
[24] Hilsenrath E and Chance K 2013 NASA Ups the TEMPO on remote sensing, and ground-based measurements of ambient fine particulate matter across North America from chemical transport modeling, satellite remote sensing, and ground-based measurements Environ. Sci. Tech. 53 5071–9
[25] Gettleman J 2020 Who gets to breathe clean air in New Delhi? (available at: www.nytimes.com/interactive/2020/12/17/world/asia/india-pollution-inequality.html?smid=em-share)
[26] Delaureaux F 2018 The Role of Transit, Shared Modes, and Public Policy in Clustering Of Pollution hotspots: Quantifying Vehicle Congestion and Air Pollution Environ. Res. Lett. 16 045311