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Air Pollution Inequality in the Denver Metroplex and its Relationship to Historical Redlining

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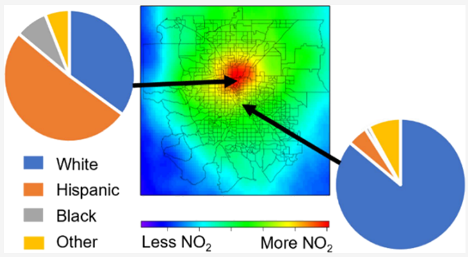
ABSTRACT: Prior studies have shown that people of color (POC) in the United States are exposed to higher levels of pollution than non-Hispanic White people. We show that the city of Denver, Colorado, displays similar race- and ethnicity-based air pollution disparities by using a combination of high-resolution satellite data, air pollution modeling, historical demographic information, and areal apportionment techniques. TROPOMI NO_2 columns and modeled $PM_{2.5}$ concentrations from 2019 are higher in communities subject to redlining. We calculated and compared Spearman coefficients for pollutants and race at the census tract level for every city that underwent redlining to contextualize the disparities in Denver. We find that the location of polluting infrastructure leads to higher populations of POC living near point sources, including 40% higher Hispanic and Latino populations. This influences pollution distribution, with annual average $PM_{2.5}$ surface concentrations of 6.5 $\mu g\ m^{-3}$ in census tracts with 0–5% Hispanic and Latino populations and 7.5 $\mu g\ m^{-3}$ in census tracts with 60–65% Hispanic and Latino populations. Traffic analysis and emission inventory data show that POC are more likely to live near busy highways. Unequal spatial distribution of pollution sources and POC have allowed for pollution disparities to persist despite attempts by the city to rectify them. Finally, we identify the core causes of the pollution disparities to provide direction for remediation.



KEYWORDS: *environmental justice, pollution, urban air, air quality, remote sensing*

INTRODUCTION

The field of environmental justice (EJ) emerged around studies of the disparities in environmental exposures and consequences for people of different race, ethnicity, or socioeconomic backgrounds.[1] Pioneering work was done by Dr. Robert Bullard, known as the Father of Environmental Justice, who showed that dumps, landfills, and garbage incinerators were much more likely to be sited in predominantly Black neighborhoods in Houston, Texas.[2] Another landmark study identified racial and socioeconomic trends around toxic waste sites, finding that while socioeconomic status played a role, race, and racism were the most important factors in the relative location of toxic waste sites.[3] These and other studies have led to numerous new policies to alleviate environmental disparities in many states,[4−8] as well as nationally,[9,10] but more work is needed to remedy the problem.[1] EJ studies made possible by the development of reliable low-cost sensors and high-resolution satellite data have consistently found that people of color (POC) in the United States are exposed to higher levels of pollution than non-Hispanic White people.[11−25] The causes of air pollution disparities are highly complex and require insight into the social and economic processes that shape demographic patterns, as well as atmospheric chemistry insights to thoroughly understand both where people live and how patterns of pollution take shape.

Histories of discriminatory policies have influenced population patterns of POC everywhere in the USA. For example, redlining was the practice by the Homeowners' and Loan Corporation (HOLC) which was created to refinance home mortgages in an effort to prevent foreclosures. In the late 1930s and early 1940s, the HOLC drew districted city maps and graded the districts on a scale of A–D in an effort to standardize the home appraisal process.[26,27] The HOLC redlining maps and appraisal processes were adopted by the Federal Housing Administration (FHA), which suppressed minoritized groups economically by refusing to insure mortgages to African Americans and anyone living in an integrated neighborhood.[28,29] Private real-estate firms, lending institutions, appraisers, and builders quickly followed suit,[30] forcing minoritized groups to remain in inner cities while refusing to provide assistance to revamp deteriorating infrastructure. In contrast, the FHA subsidized white families moving to the suburbs. Policies by the FHA, such as

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exclusionary zoning laws, have largely shaped where POC tend to live to this day.[31−33]

National and multicity studies of pollution disparities demonstrate that certain minoritized groups tend to be affected more than others, particularly people identifying as Black and African American, Hispanic or Latino, Asian and Asian American, and American Indian and Alaska Native.[19,34,35] Studies of individual cities demonstrate similar results.[18,36,37] Large-scale studies that report national or multicity averages often discuss the range of values for pollution disparities between the cities as being quite large but lack deeper insight into this phenomenon. Sociology researchers have also identified this disparity in disparities and have attributed it to the settlement patterns and urban development of individual cities, noting that residential segregation could increase or decrease a racial or ethnic group's proximity to an environmental hazard.[38] This at least partially explains the disparity in disparities, but very little work exists that specifically analyzes these traits. This study attempts to bridge this knowledge gap.

Patterns of pollution are shaped by emission sources, chemical transformations, and transport processes. In addition to the early research in the 1980s showing how toxic sites tend to be located in predominantly Black neighborhoods, sociologists have found that highways were often purposefully built through communities of color.[39,40] Siting of polluting infrastructure is not necessarily evidence of direct racism but an effect of a range of economic and political choices, such as cheaper land or less political resistance due to job creation.[41] Regardless of the reason, the effect is an inequitable distribution of pollution in many US cities. This study demonstrates that Denver, Colorado, is one such city.

The Denver-Aurora-Lakewood Metropolitan Statistical Area (MSA) consists of 12 counties in Colorado that contain almost 3 million inhabitants as of the 2020 census. The central region of this MSA consists of five immediately adjacent counties: Denver, Jefferson, Adams, Broomfield, and Arapahoe, and wholly contains the urbanized area (UA) that many consider the city of Denver, referred to in this paper as simply Denver. Denver is a rapidly growing city situated along the South Platte River, which carved a now heavily industrialized valley through the heart of Denver, serving as a route for railroads as well as Interstate 25. Surrounding Denver and extending into Wyoming, Nebraska, and Kansas is the Denver−Julesburg basin, a major source of petroleum and natural gas which has ramped up production in the past decade, making it a rapidly changing source of air pollution.[42,43] To the north of Denver is a significant agricultural operation; ammonia emissions from nearby agriculture lead to the well-known Denver Brown Cloud that appears in winter months.[44] Meteorological effects, such as wind transportation of pollutants from nighttime southwesterlies and wintertime northwesterlies, which transport agricultural emissions to the city, have a large effect on urban air pollution. Wildfires and their emissions in the western US are a growing problem in the region.[45,46] The combination of urban transportation, heavy industry, oil and natural gas drilling and processing, nearby agricultural emissions, meteorological effects, and wildfires all contributes to Denver's poor air quality, leading to violations of the National Ambient Air Quality Standards (NAAQS) for ozone: severe nonattainment for the 2008 standard and moderate nonattainment for the 2015 standard.[47,48] Complex social issues such as the history of redlining and evidence for severely segregated public schools coupled with unique air quality concerns make Denver a prime target for our EJ study.[49]

In this study, we used a multifaceted approach involving atmospheric and demographic data sources to identify race-based air quality discrepancies in Denver, Colorado. Demographic data from the 2020 census was used to provide the most up-to-date information on the racial and ethnic makeup of Denver's population; thus, this study is residential-based. Others have attempted to quantify nonresidential pollution inequalities in community-mobility studies.[50] In this study, we focus mainly on NO_2 measured by TROPOMI, as a tracer for air pollution,[51] and $PM_{2.5}$, the most deadly of air pollutants. Ambient air pollution caused over 100,000 deaths in the United States and 8.9 million worldwide in 2015 and is expected to cause more in the future.[52,53] Our study couples (i) satellite measurements, (ii) models of actual pollution distribution, and (iii) emission inventories with spatial apportionment methods to determine the levels of air pollutant concentrations and emissions to which different groups are exposed. We used this multifaceted approach to attempt to provide an accurate and comprehensive look at pollution inequality in Denver, Colorado, and insight into the emissions sources that are mostly responsible for the inequalities. We also explored why demographic patterns have emerged across the city, citing historical and sociological records to demonstrate the importance of knowing the histories and communities that are being studied.

MATERIALS AND METHODS

TROPOMI. Satellite data from January to December 2019 were downloaded from the Copernicus open access hub, which has an international open access policy. The satellite retrievals used were measured by The TROPOspheric Monitoring Instrument (TROPOMI), the payload of the Copernicus Sentinel-5 Precursor (S5P) satellite. It has been well described and evaluated previously.[54,55] We used Level 2 NO_2 tropospheric column data, version 1.4.0 with a quality assurance value >0.5 to ensure no poor-quality data or highly clouded pixels were included while keeping high-quality snow-covered scenes. Physics-based oversampling was used to produce maps at a resolution of $0.01° \times 0.01°$ at an annual average. Physics-based oversampling was done in Python using the methods of Sun et al.[56] This method involves representing TROPOMI observations as sensitivity distributions instead of points or polygons. Averaging over a sufficient time with enough data can produce markedly finer resolutions. It has been shown previously that TROPOMI tropospheric columns correlate well with various surface measurement techniques.[57,58]

Particulate Data. Annually averaged $PM_{2.5}$ data from 2019 were obtained from the Atmospheric Composition Analysis Group at Washington University in St. Louis, also at a resolution of $0.01° \times 0.01°$. $PM_{2.5}$ data were estimated from a combination of satellite retrievals of the aerosol optical depth (AOD) from the NASA MODIS, MISR, and SeaWIFS instruments and the GEOS-Chem chemical transport model. The estimations were then calibrated to regional ground-based observations of total mass using geographically weighted regression.[59,60]

Stationary and On-Road Source Emissions. The previously developed Fuel-based Inventory for Vehicle Emissions (FIVE) was used as an estimate of on-road vehicle emissions and captures emissions from light-duty gasoline vehicles, heavy-duty diesel vehicles, and buses.[61,62] The FIVE inventory normally aggregates roadway-link level traffic data and population density maps to a 4-km resolution grid, such that these metrics can be used as spatial surrogates when distributing fuel consumption and emissions to a gridded map. In this manuscript, the roadway-link level traffic data and population data used for spatial surrogates have instead been reaggregated at a 1.3-km resolution to produce higher resolution emissions to better match with the high resolution of oversampled TROPOMI data and small areas of census tracts in the Denver area. The FIVE data are provided for weekdays, Saturdays, and Sundays in each month of 2019 and have been averaged for the entire year into Weekday and Weekend categories and then spatially averaged in each census tract. National Emissions Inventory (NEI) point source data for all emitters of criteria air pollutants in the metroplex were downloaded from the EPA Web site and mapped using Python and ArcGIS.[63] Population fractions were areally apportioned and weighted by the emissions intensity for the particular pollutant. Separately from FIVE, Highway, and Major Road traffic count data and estimates were provided by the Colorado Department of Transportation (CDOT),[64] which included traffic count, road type, width, and other data provided in variable-length segments. These data were weighted by both the road length and average annual daily traffic (AADT).

Demographic Data. 2020 Census data were downloaded at the census tract and census block level for "Race and Hispanic or Latino", and "Not Hispanic or Latino by Race" data sets from the IPUMS National Historic Geographic Information System archive alongside the 2020 census boundaries as an ESRI Shapefile with projected geometry style EPSG:4326.[65] Data were mapped using the Python libraries Pandas, Geopandas, Matplotlib, and ArcGIS ArcMap 10.8.2.[66−68] The demographics most discussed in this paper are as follows: Non-Hispanic White, American Indian and Alaska Native, Asian and Asian American, Black or African American, Native Hawaiian and Pacific Islander, Some Other Race, Two or More Races, and Hispanic or Latino. All categories of races are non-Hispanic in ethnicity, except Hispanic or Latino. UAs are, as defined by the US Census Bureau, a continuously built-up area with a population of 50,000 or more, comprising one or more central place(s) and the adjacent densely settled surrounding areas consisting of other places and nonplace territory. Daouda et al.[12] describe the pitfalls of assuming the relationship between air quality and racial or ethnic group population to be linear. They show that $PM_{2.5}$ concentration increases with an increased fraction of people who identify as Black and African American, but a linear fit did not describe the data well at all.[12] Additionally, the fractional population data, which would be used in a linear regression, are highly skewed, making linear regression impossible. Instead, we use Spearman correlations, a type of rank-order correlation, between fractional demographic population and average NO_2 column.[69] Areal apportionment, described in detail by Mohai and Saha, is a method used by sociologists to determine if the placement of polluting infrastructure was unequal.[70] We used finely resolved racial and ethnic demographics in census blocks and locations of point sources within the same communities. Point source locations are buffered to a specified distance, and proportional amounts of blocks that partially fall within the distance are averaged to find the approximate population demographic breakdown immediately around a point source.[24]

Redlined Districts. Denver redlined districts data were downloaded from *Mapping Inequality*, a University of Richmond effort to convert historical redlining maps and forms to electronic format.[71] The data were downloaded as ESRI shapefiles and mapped using Python. In 1938, the city of Denver was mapped by the HOLC, divided into districts, and graded on a scale from A (Best) to D (Hazardous), with districts graded D overwhelmingly being populated by POC and minoritized ethnic groups. These maps were used to deny services to the inhabitants of the lower-graded regions, including lending services, healthcare, and retail businesses, such as supermarkets. This practice is known as "Redlining" for the red color used for filling in the "Hazardous" neighborhoods on the maps.[14,26,27,72] To place the Denver analysis in perspective, the Spearman correlation for each racial and ethnic group with TROPOMI NO_2 columns (at a resolution of $0.01° \times 0.01°$) was calculated for every US city that the HOLC districted in the late 1930s. This represents almost 200 cities of various sizes and minority distribution patterns in almost every region of the US. The modern UAs of the historically red-lined cities were used as boundaries for satellite data calculation. The original ∼200 cities were truncated to 150 when considering cities that have merged into the same UA, such as Quincy, MA and Revere, MA, both now being coupled into the greater Boston UA. Additionally, five red-lined cities have not achieved the definition of "urbanized area" for any census tracts and were left out of the analysis.

RESULTS AND DISCUSSION

Air Pollution Discrepancies in Modern Population Demographics. The population of POC around Denver is best described as a clustered distribution,[73] with three distinct areas with higher proportions of POC, as seen in Figure 1a.

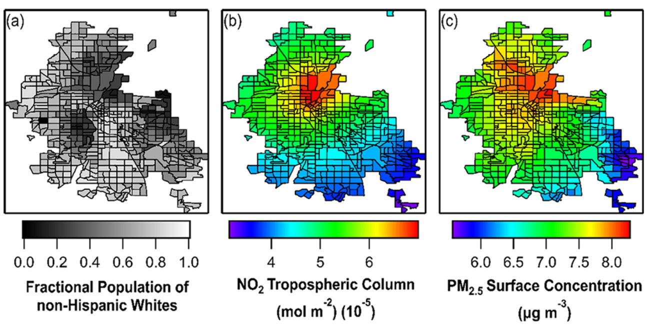

Figure 1. Map of the Denver Metroplex population fraction of people who identify as non-Hispanic White (a) where lightly shaded areas have higher proportions of people who identify as non-Hispanic White and darkly shaded areas have higher proportions of people who identify as a person of color. Representative NO_2 tropospheric column (b) and $PM_{2.5}$ surface concentration (c) maps. Black lines are census tracts contained within Denver's UA.

The three areas are distributed around the center of the city, and in between them is an area of a high density of people who identify as non-Hispanic White. Oversampled TROPOMI data were used to map the NO_2 distribution throughout the Denver metroplex with a resolution of 0.01° (∼1 × 1 km at this latitude).[56] With this fine resolution, it has been shown that we can resolve differences between census tracts.[18−20] The data in Figure 1b show higher average NO_2 columns over the center portion of the city, mostly centered on Commerce City and North Washington areas, both a part of Adams County, with

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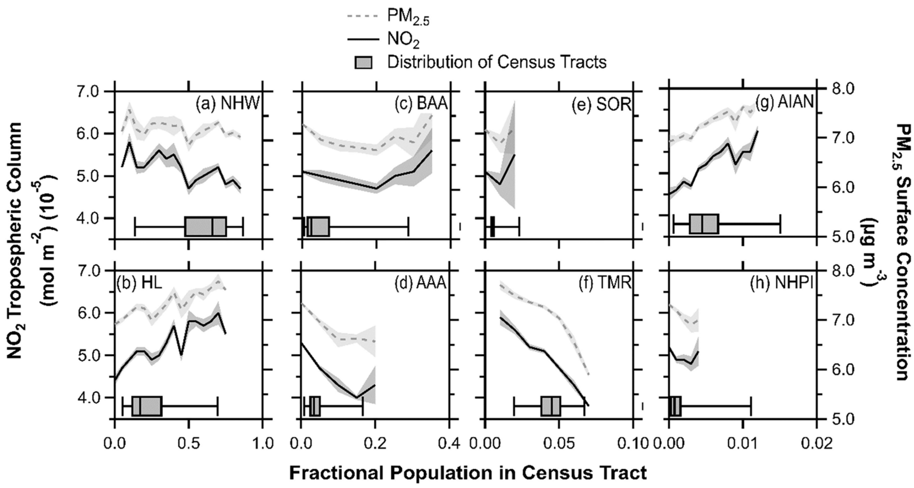

Figure 2. Binned averages for every specified fraction of a particular demographic group showing increase or decrease of the NO_2 tropospheric column and $PM_{2.5}$ surface concentration with increasing population fraction. Bins are 0.05 fractional increase for non-Hispanic White; Hispanic or Latino; Black and African American; and Asian and Asian American groups, 0.01 for some other race and two or more races groups, and 0.001 for American Indian and Alaska Native and Native Hawaiian and Pacific Islander groups. Shaded regions depict standard error. Box and whisker plots depict the distribution of census tract fractions. Vertical line is the median, boxes are middle quartiles, and whiskers are 2nd and 98th percentile. Box and whiskers may not line up with pollutant lines due to population binning. Abbreviations: NHW: non-Hispanic White, HL: Hispanic or Latino, BAA: Black and African American, AAA: Asian and Asian American, SOR: Some other race, TMR: Two or more races, AIAN: American Indian and Alaska Native, NHPI: Native Hawaiian and Pacific Islander.

Table 1. Spearman Coefficients for Each Correlation Calculated between the Fraction of Denver Census Tract Demographic and NO_2 Tropospheric Column or $PM_{2.5}$ Surface Concentration, Population-weighted Average, and Population Statistics for Each Racial or Ethnic Group[a]

racial or ethnic group	spearman coef. (p value)		pop. wtd. ave.		pop. stats	
	NO_2	$PM_{2.5}$	NO_2 (mol m^{-2}) ($\times 10^{-5}$)	$PM_{2.5}$ ($\mu g\ m^{-3}$)	tot. pop.	pop. frac.
non-Hispanic White	−0.22 (<0.001)	−0.13 (0.003)	4.98 + 0.04	7.18 + 0.03	1,654,648	59.8%
Black and African American	−0.02 (0.7)	−0.14 (0.001)	4.93 + 0.03	7.00 + 0.03	152,573	5.5%
Asian and Asian American	−0.45 (<0.001)	−0.42 (<0.001)	4.78 + 0.04	7.00 + 0.03	132,337	4.8%
American Indian and Alaska Native	0.42 (<0.001)	0.40 (<0.001)	5.24 + 0.03	7.33 + 0.02	12,824	0.5%
Native Hawaiian and Pacific Islander	−0.13 (0.002)	−0.21 (<0.001)	4.90 ± 0.03	6.97 + 0.03	4,463	0.2%
some other race	−0.07 (0.1)	−0.10 (0.03)	5.03 + 0.04	7.17 + 0.03	13,859	0.5%
two or more races	−0.40 (<0.001)	−0.37 (<0.001)	4.95 ± 0.04	7.12 ± 0.03	122,175	4.4%
Hispanic or Latino	0.39 (<0.001)	0.33 (<0.001)	5.28 ± 0.03	7.32 ± 0.02	671,821	24.3%

[a]Uncertainties in population-weighted average are standard errors of the mean.

columns two times larger than other areas of Denver. Heavy refining industries and highway traffic, centered on Commerce City and surrounding the central business district including slower traffic and diesel-powered vehicles, contribute to the NO_x precursor emissions for NO_2. To the north of the city, and outside the maps in Figure 1, is a significant oil and gas drilling operation on the Denver−Julesburg basin, which is known to influence O_3 production in the area by emitting NO_x and VOC precursors.[74,75] Meanwhile, residential areas with less traffic and more service industry tend to have lower NO_2 columns. The annual average of TROPOMI data used here averages across seasons, where exact NO_2 may differ. The average was used here to quantify what communities experience.

Fractional populations were calculated to normalize population differences between census tracts and then plotted compared to the average NO_2 tropospheric column in each census tract within the Denver-Aurora UA. Data were binned into 0.05, 0.01, or 0.001 fractional population width bins, and a line was drawn through the average of each bin, summarized in the black lines in Figure 2. The average NO_2 column tends to be lower in census tracts where more people identify as non-Hispanic White; Asian and Asian American; and as two or more races. It should be noted that there are more census tracts with higher fractions of people who identify as non-Hispanic White because this demographic makes up a majority in Denver (59.8% of total population according to the 2020 census). This trend is reversed for some other racial and ethnic groups, with especially pronounced differences in people who identify as American Indian and Alaska Native and Hispanic or Latino. For the former, a very strong increase occurs over a small span of population fraction, indicating that this population is especially disproportionally impacted by poor air quality. For the latter, the increase is more gradual over a much larger range of the population fraction.

The dashed gray data in Figure 2 shows the same trends but with a $PM_{2.5}$ distribution from Donkelaar et al., who use a combination of AOD satellite retrievals, ground measurements, and modeling to prepare high-resolution $PM_{2.5}$ concentration maps. $PM_{2.5}$ is a more directly health-relevant pollutant and shows a remarkably similar correlation pattern with fractional populations as NO_2, though the enhancements are somewhat

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lower in magnitude. The robust correlation with NO_2 is interesting as small amounts of $PM_{2.5}$ are often coemitted with NO_x ($NO + NO_2$) from stationary and on-road combustion sources, but a significant portion of $PM_{2.5}$ is a result of secondary formation from precursors that are also emitted. The similarity of NO_x and $PM_{2.5}$ pollution distribution (Pearson correlation $r = 0.87$, p value < 0.001) suggests a potential relationship that could be exploited to measure $PM_{2.5}$ distribution indirectly using NO_2 satellite retrievals in areas with a high proportion of $PM_{2.5}$ nitrate where NO_2 is a precursor.

These data show that census tracts with higher proportions of people who identify as Hispanic or Latino and American Indian and Alaska Native tend to have worse air quality. This is not a new finding; many other studies have found an air quality discrepancy with respect to race and ethnicity.[14,16,18,21,25,37,76−81] Population-weighted averages, while easy to calculate, sometimes mask important distributional insights in the data.[80] Table 1 presents the Spearman correlation between NO_2 column and surface $PM_{2.5}$ concentration with racial or ethnic group population fraction in census tracts in Denver. Spearman correlations were used to determine the existence of a correlation between racial/ethnic groups and NO_2 or $PM_{2.5}$, not the strength of the increase or decrease in pollution. Due to the skewness of the population fraction data, more robust linear regression or Pearson correlation is inappropriate for this application.

There are several moderately strong correlations observed between air quality and the demographic population fraction of several racial and ethnic groups. The most highly correlated groups are (i) the positive correlations between NO_2, $PM_{2.5}$, and the fraction of American Indian and Alaska Native and Hispanic or Latino race and ethnic groups. (ii) The anticorrelation between NO_2, $PM_{2.5}$, and the fraction of non-Hispanic White; Asian and Asian American; and two or more races groups, indicating that there tends to be relatively less pollution in census tracts with more people identifying with these groups.

Figure 3 shows the distribution of Spearman coefficients calculated for 150 red-lined cities in the US. The most striking feature of this figure is the distance between non-Hispanic White quartiles and the zero-line compared to every other racial and ethnic group. Over 87% of cities studied showed a negative correlation for the non-Hispanic White group. The Spearman correlations calculated for Denver are not quite representative of the average US city, with only Hispanic or Latino; people of some other race; and non-Hispanic White groups falling within one quartile. Denver appears to be better than many other US cities, with Spearman coefficients closer to zero or negative values than the average for all groups except Hispanic or Latino and American Indian and Alaska Native. The Black and African American; Asian and Asian American; and people of two or more races racial group medians across redlined cities are much larger than the correlation calculated for Denver (Black and African American: 0.32 vs −0.02, Asian and Asian American: −0.16 vs −0.45, people of two or more races: −0.05 vs −0.40 for NO_2 tropospheric column). For the Asian and Asian American and people of two or more races racial groups, this shows a moderate anticorrelation. This figure shows that for many non-White racial and ethnic groups, there is a positive correlation between their population fraction and air quality in many US cities. The reasons for the groups that experience less environmental pollution discrepancies in Denver than in other cities is complicated and historical. Each individual city likely requires its own historical analysis to determine why people live where they do and how modern infrastructure benefits or detriments them. For example, the settlement patterns of Hispanic or Latino communities in Denver were largely affected by the sugar beet boom in the early 20th century, and the influx of manufacturing jobs (and the locations of those jobs) during World War II.[82] For people who identify as Asian and Asian American, violent race riots in the late 19th century and nearby WWII era Japanese concentration camps influence where Asian and Asian American communities are located today.[83] Additionally, the annually averaged data used in this study may paint cities in a slightly worse light if their populations identifying as nonwhite live in more spread out locations due to shorter NO_2 lifetimes and more localized emissions spreading in warmer months. The inequality in air pollution for different ethnic groups in Denver shown in Figure 3 introduces two major questions: Where do minoritized racial and ethnic groups in Denver live and why? And what are the sources of pollution that cause the discrepancies? To answer these questions, we first looked at the history of redlining in Denver and its present-day consequences, and then studied inequalities in air pollutant emissions in Denver with an eye toward solutions.

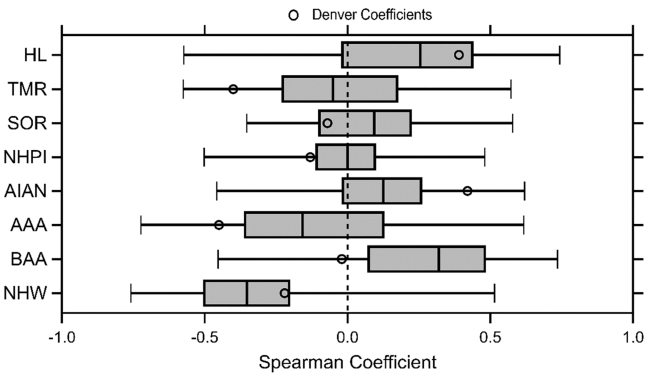

Figure 3. Distribution of Spearman coefficients in the UA of 150 redlined cities shows moderately negative correlation between TROPOMI NO_2 columns (0.01° × 0.01° resolution) and non-Hispanic White population fraction and weak-moderate positive correlations between all other demographic groups. Vertical line shows median; boxes show middle quartiles, and whiskers show the 2nd and 98th percentile. Open circles show the Denver Spearman coefficients. Abbreviations: HL: Hispanic or Latino, TMR: two or more races, SOR: some other race, NHPI: Native Hawaiian and Pacific Islander, AIAN: American Indian and Alaska Native, AAA: Asian and Asian American, BAA: Black and African American, NHW: non-Hispanic White.

Historical Perspective on Air Quality Disparities. The geographical distribution of people in a city is a result of many competing factors. One historical factor that influences the population patterns of minoritized groups in the metroplex is the history of redlining. When redlining was implemented in Denver in 1938, the city was growing rapidly and would for decades to come, which has now placed all of the formerly redlined districts firmly in the center of the city. Though the practice of redlining was outlawed by the Fair Housing Act of 1968, alternative exclusionary practices remained in place. In Denver, an important exclusionary practice was racial covenants: neighborhood-level documents that defined standard practices, such as lot sizes and setbacks, also contained

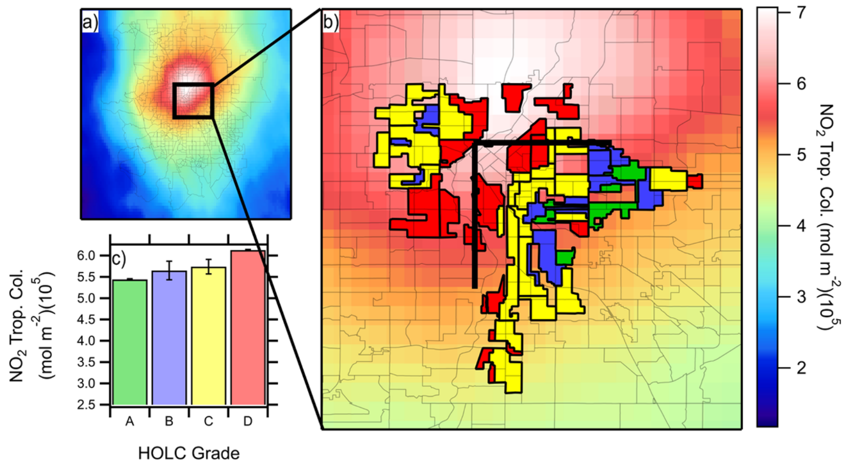

Figure 4. Oversampled TROPOMI data averaged across original 1938 financial securities map districts show increasing NO_2 column with decreasing grade A–D. Grid points were averaged proportionally to their area inside each district, then averaged together with their like-graded districts, weighted proportionally to the district areas. (a) Oversampled TROPOMI map of the area, (b) same TROPOMI data zoomed to the center over the HOLC districts, and (c) depicts the annual spatial average of the TROPOMI NO_2 columns for each HOLC district type. Origin value of 2.5×10^{-5} mol m^{-2} is the annual average regional background for this area. Error bars show the standard error. The thick black corner represents the inverted L.

clauses that occupants cannot sell or rent their properties to certain racial groups. The neighborhood known as Burns Brentwood has a racial covenant that says "Only persons of the Caucasian race shall own, use or occupy any dwelling or residence···" and specifically carves out an exception for "persons of another race who are employed as domestic servants".[84] Additionally, cities had already built up around the HOLC maps and the unequal placement of polluting infrastructure has left these areas continuously disadvantaged, as has been observed directly in Houston, Texas, and elsewhere in the US.[1,2] Even though all the HOLC districts are now deep in the center of Denver, with the growth of suburbs and exurbs all around and the relatively equal potential for polluting infrastructure to be located anywhere, there are still measurable air quality differences between them and the rest of the city, as shown in Figure 4. NO_2 column data from TROPOMI was overlaid with the original bounds of the HOLC districts, and the columns were averaged for each district. Finally, the area-weighted average was calculated and presented in Figure 4c, where the difference between districts formerly graded A and D is significant despite both being in the city center, with D-graded districts having an NO_2 column 13% higher than A-graded districts. This difference is on the low end compared with other cities across the US according to Lane et al., who utilized modeled NO_2 distributions as opposed to satellite retrievals.[14]

Generally, redlining is considered to have most affected people who identify as Black and African American.[27] Of the 16 districts graded "D" in Denver, only three of these districts appear to have been drawn around predominantly Black and African American areas. The influence of neighborhood covenants and other exclusionary zoning techniques predating redlining left Black and African American communities in Denver compressed into too-small neighborhoods.[85,86] More spread out through the metroplex at the time were Eastern European immigrants and their descendants, Italians, Mexican and New Mexican agricultural workers, and a few Japanese truck farmers (a kind of small agricultural operation that grows vegetables for sale at local markets). Due to the diversity of industries and the people who provided the labor for them, the red-lined maps in Denver affected more than just the Black and African American community.

Denver has retained some of the population patterns outlined by the HOLC, but more recently, city officials have been making efforts to mitigate this pollution and air quality disparity. The city has planted trees and developed parks in disadvantaged neighborhoods and established the Love My Air initiative.[87,88] Minority populations still tend to be high in the former red-lined areas, but the pattern goes by a different name now—the "Inverted L", which is a well-documented geographic area that divides the city of Denver. South and east of the L, it is observed that there is a higher proportion of people who identify as non-Hispanic White who are less likely to be displaced (forced to leave either directly, i.e., eminent domain, or indirectly, i.e., neighborhood becomes too expensive), more likely to vote, less likely to develop asthma, and enjoy a greener living environment.[89−92] Meanwhile, to the north and west of the Inverted L, the opposite is true.

Sources of Air Quality Discrepancy. It has been previously shown that mobile sources of pollution are the greatest factor in pollution discrepancies, primarily diesel-powered vehicles.[19,93,94] This recent research has prompted several states to pass laws, and the EPA to overhaul rules, concerning diesel-powered vehicles.[95−97] Figure 5a shows NO_x emissions from on-road motor vehicles on weekdays in Denver over the course of a year, estimated by the FIVE inventory. The NO_x emissions are centered around northern Denver County, north of I-70 in the Chaffee Park, Globeville, and Elyria-Swansea neighborhoods that are adjacent to heavy industry and petrochemical refining that occurs in Commerce City. Weekend NO_x emissions are predictably much lower but follow a similar pattern to weekdays, shown in the Supporting Information, Figure S4. Despite making up only ~3% of vehicle sales in the United States, the diesel-powered fleet emits comparable amounts of NO_x to the gasoline-powered fleet of vehicles.[98] Because diesel-powered vehicles tend to be used for commercial purposes, we observe a much larger decrease in the level of NO_x emissions from diesel vehicles on weekends. Despite this difference, diesel-powered vehicles emit 48% of on-road-sourced NO_x in Denver. When considering

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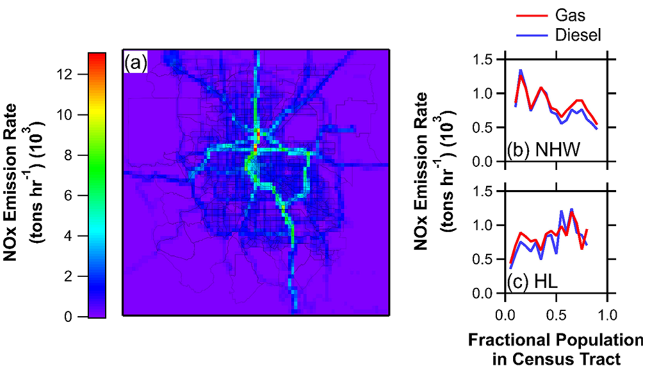

Figure 5. Averaged FIVE data mapped to census tracts and compared to fractional populations show that vehicle emissions are higher in census tracts with a higher proportion of people who identify as Hispanic and Latino. The map (a) shows the NO_x emission rate at a resolution of 1.3 km averaged over 1 year. NO_x emission rate averaged across census tracts compared with the fractional populations of non-Hispanic White (NHW) (b) and Hispanic and Latino (HL) (c) groups.

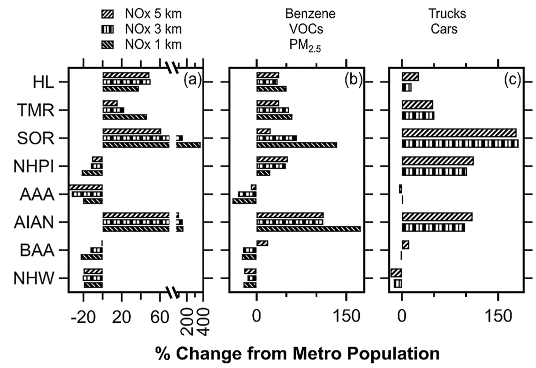

Figure 6. Areal apportionment of NEI point source and highway data shows that lower proportions of people who identify as non-Hispanic White tend to live near hazards than those who live in Denver as a whole. NO_x emissions (a) were apportioned at variable distances and weighted by total NO_x emission. Other NEI emissions (b) were apportioned 1 km from each point source and weighted by their respective pollutant emissions. Highway segments (c) were apportioned 500 m from road centerlines and weighted by AADT estimates by CDOT.[101] Abbreviations: HL: Hispanic or Latino, TMR: Two or more races, SOR: Some other race, NHPI: Native Hawaiian and Pacific Islander, AIAN: American Indian and Alaska Native, AAA: Asian and Asian American, BAA: Black and African American, NHW: non-Hispanic White.

FIVE on-road and off-road inventory and NEI 2017 stationary sources, on-road emissions of NO_x make up 70% of the NO_x emitted in this region.

The interstate highways that carry this dense polluting traffic were built from the late 1940s until 1993, well after the establishment of racial enclaves in the city. It has been noted by sociologists that highways were sometimes purposefully built through neighborhoods of color.[39,99] In Denver, the South Platte River Valley Superhighway, now known as I-25, was constructed to bisect the Globeville and Argo neighborhoods, named for the heavy metal smelteries that occupied those neighborhoods. At the time, the populations of these neighborhoods were largely Eastern European, but after construction began, an exodus occurred leaving housing open for Hispanic and Latino immigrants and residents and others, making these some of the most racially diverse neighborhoods in all of Denver.[100] Figure 6c shows how population fractions of POC are larger around highways. People who identify as non-Hispanic White make up 59% of the population of Denver but only 55% of the population of those living within 0.5 km of highways or major roads. When populations around highways are weighted for AADT, only 52% (Wilcoxon rank-sum p value < 0.001) of people who live within 0.5 km identify as non-Hispanic White, and when weighted for truck traffic specifically, this drops to 49% (Wilcoxon rank-sum p value < 0.001). This small but measurable difference, combined with the FIVE inventory census tract averages, show that POC are shouldering a disproportionate burden of air pollution, driven at least in part by inequitable city planning practices decided decades ago, which dictates where gas powered, and especially where diesel-powered vehicles pollute the most. This represents highways, but also industrial corridors around more heavily industrialized areas such as Commerce City where transport by diesel truck is common.

In addition to mobile sources of pollution, stationary sources are spread throughout the metroplex. The NEI contains the emissions of harmful products from all stationary sources, including emissions that we have not yet examined, such as VOCs and other harmful air pollutants. Together, NO_x and VOCs produce particulate matter and ground-level ozone, another health concern. We find that, when comparing the demographic profiles around point source emitters in Denver using areal apportionment, weighted by emissions and averaged, that the demographic profile no longer resembles that of the city as a whole.[70] Figure 6a,b show the direct emission discrepancy around point sources. The profile consists of more POC, especially people who identify as American Indian and Alaska Native, but almost all minoritized racial and ethnic groups at variable distances. This technique was also used with VOCs, benzene, and fine-particle direct emissions. For all pollutants, people who identify as non-Hispanic White and Asian and Asian American live less frequently in the communities immediately surrounding large emission sources than in Denver as a whole. Meanwhile, people who identify as Black and African American are more likely to live near large sources of benzene emissions but slightly less likely to live near sources of VOCs or $PM_{2.5}$. People who identify as some other race according to the US census category, which consists of many people who do not fit well into another census category, such as many Latinos, Middle Eastern/North African, and Afro-Caribbean people, are much more likely to live near larger sources of primary $PM_{2.5}$. Finally, the largest increase in likelihood of proximity for each benzene, VOCs, and $PM_{2.5}$ is experienced by people who identify as American Indian and Alaska Native.

Figure 6 shows that, in addition to the distribution of pollution being unequal, the placement of polluting infrastructure is also unequal. Because of this, there may be several unique air pollution environments around the metroplex. Different VOCs and levels of NO_x could allow for distinct regions with more or less VOC oxidation potential and unique blends of VOCs and oxygenated VOCs. Future studies would be prudent to map and speciate VOCs around a cityscape at a high spatial and time resolution, beyond the current capabilities of satellite measurement.

We have shown that the city of Denver places a disproportionate burden of air quality on the shoulders of

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certain minoritized racial and ethnic groups, as has been observed in many cities in the US and around the world. These disparities exist because of where the most affected racial and ethnic groups tend to live, which is dictated by historically discriminatory practices such as redlining, racial covenants, real estate steering, and other exclusionary zoning laws—adversely impacting communities of color with worse conditions while preventing them from leaving for better housing. The sources of pollution are well-known and show a bias in placement; both NEI point sources and highways have larger proportions of certain groups of POC living in the communities around them than living in the city as a whole. Similarly, TROPOMI NO_2 columns and modeled $PM_{2.5}$ concentrations both show ambient pollution disparities with regard to race and ethnicity.

When considering national aggregate studies that measure air pollution disparities, the city of Denver appears to break the trend. People who identify as Black and African American or Asian and Asian American bear comparatively less of the air pollution burden than other non-White communities in Denver. Explanations for these differences lie in the history of Denver and in how and why certain racial and ethnic groups live where they do. We encourage other environmental researchers to carefully consider the histories of the places they study to form a complete picture in order to properly characterize the pollution disparities.

Some argue that characterization of the problem is not enough, and it is time to move toward addressing the inequalities.[102] Recent air quality modeling results suggest that national average racial-ethnic inequalities can be eliminated with modest emission reductions (~1% of total emissions) using a location-specific approach rather than the two main regulatory strategies that are currently employed by the U.S. EPA and state/local air pollution agencies (i.e., State Implementation Plans to meet NAAQS and sector-specific Best Achievable Control Technology [BACT] requirements).[103] California has taken such an approach with 14 communities to date,[104,105] using a variety of strategies that include local rules and ordinances, targeted enforcement, support for small- and medium-sized businesses to reduce toxic emissions, clean technology incentives, new construction buffer zones,[106] alternative truck routing, exposure mitigation,[107] and grants for community-based organizations to build capacity and partner with government agencies. This approach augments state-wide regulations focused on mobile sources, such as diesel engine retrofit requirements for NO_x and PM reduction[108] and an enhanced heavy-duty vehicle inspection and maintenance program that includes roadside emissions monitoring.[109]

Colorado has been a leader in using remote sensing technologies to identify high-emitting passenger cars[110] and plans to electrify all on-road light-duty vehicles statewide by 2050, with the adoption of medium- and heavy-duty zero-emission vehicles to at least 30% of new sales by 2030 and 100% of new sales by 2050.[111] The Regional Transportation District in Denver has implemented a free public transportation measure in some high-ozone summer months to attempt to increase public transit ridership.[112] One part of the solution may be prioritizing the conversion of diesel-powered vehicles to zero-emission technologies in Denver's most pollution-impacted communities, which could reduce inequalities from mobile source emissions. Other targeted emission reductions in the areas north and west of the inverted L could reduce pollution disparities in Denver's fenceline communities.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c03230.

Pollution inequality vs income plots, redlined city Spearman coefficients, and FIVE weekend emission plots (PDF)

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Notes

The authors declare no competing financial interest.
FIVE emissions data used in this study is available at https://csl.noaa.gov/groups/csl7/measurements/2020covid-aqs/emissions/

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