Effects of Air Quality Disparities on Youth Asthma in the San Francisco Bay Area

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ABSTRACT

BEACO$_2$N air quality sensors in the San Francisco Bay Area blanket locations with a high-density network, capturing neighborhood-levels of carbon dioxide (CO_2) and aerosol concentrations. In this study, I interpolated and spatially analyzed aggregated seasonal averages from 2016 to 2019 in ArcMap, and then examined these interpolated air pollutant concentrations in the context of community health metrics: asthma emergency room (ER) visits among children, race and ethnicity, and income. Concentrations of CO_2 and aerosols and income had strong associations, while relationships with race/ethnicity percentiles varied seasonally in their trends and statistical significance. Aggregated seasonal CO_2 concentrations and emergency room visits due to asthma had an inconsistent, yet statistically significant relationship. Associations between asthma ER visits and race/ethnicity, and asthma ER visits and income were the strongest, most consistent, and statistically significant ($p < 0.05$). My analysis indicates that low-income and marginalized communities often bear a higher poor air quality burden, related to higher rates of asthma ER visits, especially for children. In semi-structured interviews with asthmatic youth, youth participatory action research (YPAR) and general research involvement benefitted participants in their understanding of and coping with their asthma. Generally, participants involved in YPAR expressed a greater interest and awareness of environmental justice themes. Community organization and involvement are a vital lens through which to further understand the disproportionate impacts of air pollution and to provide experiential information for health regulations. This study provides a foundation for future discussion, partnership and community organizing with community members impacted by youth asthma.

KEYWORDS

environmental justice, particulate matter, public health, health disparities, mixed methods

INTRODUCTION

Anthropogenic pollutants in the environment affect the well-being of all communities. An estimated 9-23 million and 5-10 million asthma-related emergency room visits in 2015 are attributed to exposure to ozone and 2.5-micron particulate matter respectively (Anenberg 2018). These and other air pollutants can cause respiratory and cardiovascular diseases, reproductive and central nervous system dysfunctions, and cancer through acute or ambient exposure (Manisalidis et al. 2020). Environmental disparities in air quality disproportionately affect communities based on income, race, and ethnicity, especially in California (Bowen 2001). Children have an increased susceptibility to health risks from low levels of air pollutants compared to other age groups as a result of their undeveloped respiratory systems, making marginalized and low-income children especially more vulnerable to environmental disparities in airborne pollutants (Lee 2017, Triche et al. 2006, Boyce and Pastor 2013). Climate change and interacting cumulative environmental health disparities will continue to worsen the health impacts of air pollution.

In addition to this already present concern for the overall global population, minority children living in urban areas, who are exposed to air pollutants, are especially at risk. Typically, lower income and minority groups are more likely to live near roads with heavy traffic (OEHHA 2020 a). Asthma rates correlate to one's proximity of residence to traffic, where in areas of the highest exposure, asthma rates are two times higher (Seltenrich 2019). Thus, asthma and environmental hazards that exacerbate asthma disproportionately impact communities of color in California (Nardone et al. 2020). Redlining, a historical systematic practice of housing discrimination in both the federal government and private sector through loans and interest rates, although made illegal, has been shown to still affect housing and city planning (Nardone et al. 2020). Historically residentially redlined communities in California had 2.4 times higher median rates of emergency department visits due to asthma within their census tract (Nardone et al. 2020). Racial and economic inequality characterized a disproportionate environmental burden in the Bay Area when information was synthesized from the Toxic Release Inventory (Pastor et al. 2007).

Black people, Indigenous people, people of color, and lower-income people will continue to face an unequal burden of this pollution, whether due to increased vulnerability, such as with children, or because of ingrained environmental inequalities due to socioeconomic factors, lack of regulation, and lack of representation (Pastor et al. 2010). Research must aim to uplift marginalized communities that are facing these disproportionate burdens, while engaging with them to allow for mutually increased knowledge towards equitable environmental and public health, empowerment, and advocacy (Pastor et al. 2010). Hybrid qualitative and quantitative methods are especially valuable to understanding a fuller picture of environmental health, as community narratives give increased knowledge as to how people are actually experiencing environmental health stressors (Brown 2003). Utilizing community-engaged approaches better accounts for the cumulative impacts of environmental and social stressors and can lead to increased benefits to vulnerable populations (Morello-Frosch and Balazs 2020).

Neighborhood-level air quality can be a challenge to measure due to either sparse monitoring networks or unrealistic modeling (Mijling 2019). BEACO_2N has a different approach in comparison to other networks, because BEACO_2N blankets interesting representative locations with a high-density of sensors (BEACO_2N 2020). Although BEACO_2N data has not been spatially modeled in this way previously, I employed the methods in CalEnviroScreen 3.0 to produce a geospatial model of long-term BEACO_2N data (Zeise and Rodriquez 2017). Many BEACO_2N sensors are on the roofs of schools, and when possible this is paired with a curriculum to teach K-12 students about greenhouse gases (BEACO_2N 2020). It is important to track air pollutants over time in a changing climate with various methods and networks, to explore the most cost efficient and accurate monitoring methodology and to prove if regulations and policy are beneficial to populations. Information on environmental disparities in air pollution in the Bay Area must be updated and contrasted using different network strategies, while pairing these analyses with crucial community perspectives of those affected by environmental injustice.

The aim of this study is to utilize geospatial modelling results with this high-density air quality network in the San Francisco Bay Area to: compare this model to other studies with generally lower density networks; to update previous research on this environmental justice issue with more recent data and analysis; and to inquire about perspectives and emotions of resistance in affected individuals. I use geospatial analyses to investigate correlations and trends in between interpolated long-term CO_2 and aerosol concentrations over several years, aggregated emergency department visits due to asthma in children, percentiles of races and ethnicities, and median household income. This analysis explores how demographics and socioeconomic factors relate to the distribution of air pollution burdens at the census tract level to inspect which regions may be impacted most by disparities in air quality. Next, I investigate how seasonal long-term air quality is related to aggregated emergency visits due to asthma in children, and how asthma visit rates relate to race/ethnicity and income across census tracts. To examine how public perceptions align with or differ from current research and policy and if a greater sense of control over potential asthma triggers is associated with increased environmental justice awareness and community mobilization, I conducted interviews with children in Richmond with asthma to compare between those that have participated in a Youth Participatory Action Research program on environmental justice with those that have not. Semi-structured interviews, paired with a novel network approach to analyze long-term air quality in communities, help capture a more comprehensive assessment of air quality impacts on asthma to account for other social, mental and emotional factors that may act synergistically or community actions that may be beneficial.

BACKGROUND

Air pollutants and BEACO$_2$N

Air pollutants, such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and aerosols or particulate matter (PM) are typically primary health concerns. Black carbon (BC) is also largely discussed in areas with industrial pollution. Yet, due to the Drayage Truck Regulation, trucks with diesel particle filters have increased and engine ages have decreased, resulting in a decrease in fleet average BC and NO_x (oxides of nitrogen) (Preble et al. 2015). This change may suggest a shift in concerns over time from larger-sized diesel particulate matter and black carbon emissions to smaller, ultrafine particles. In modeling urban air pollution, one must use a dense network of sensors to acknowledge the localization and atmospheric dispersion of air pollutants (Mijling 2019). For example, with PurpleAir sensors, there is a lack of sampling continuity and representation, typically resulting in higher measurements (Bi et al. 2020). Contrastingly, the BEACO$_2$N network has a distinctively high spatial density (Shusterman et al. 2016). Although these sensors were made with the primary intention to evaluate urban greenhouse gas emissions, the available measurements on aerosols and CO_2 can be used to create a spatial grid of micro-scale pollution to model exposure rates of related pollutant species that affect asthma. Even though CO_2 is not directly attributed to adverse respiratory health outcomes, it is analyzed as a proxy for hazardous co-pollutants such as SO_2 and NO_x (Boyce and Pastor 2013).

Many of the Berkeley Environmental Air quality and CO2 Network (BEACO_2N) locations are located on the roofs of schools, which make this research especially significant for children with asthma in the Bay Area. Analyzing air pollutants near schools is particularly important, as inadequate indoor filtering systems and other indoor air hazards can exacerbate poor outdoor air quality (Shendell et al. 2009). Attending schools nearby major roadways with poor air quality is associated with higher minority populations, exacerbations of asthma and chronic bronchitis, and lower academic performance, oftentimes due to these stressors (Pastor et al. 2006).

Environmental justice framework

This research aims to contribute to environmental justice scholarship, as the field evolves from solely assessing empirical evidence to incorporating activism, social science, and emotional harm (Holifield et al. 2009). Mixed methods are employed to merge postpositivist and advocacy/participatory worldviews and to evaluate cumulative environmental and social stressors from air pollution (Cresswell 2009). Environmental sociology, which originated around 1972, is crucial in environmental justice research, to assess individual and community impacts of environmental degradation and to understand how mental health impacts act additively to physical health effects within the cultural, social, and historical context of the community (Brown 2003). This work also hopes to challenge post-racial and colorblind ideologies, that attribute racism only to intentional discrimination (Salim 2020). In the U.S. legal system, environmental justice law allows reparations to be sought through tort law or Title VI of the Civil Rights Act of 1964 (Salim 2020). These two methods of reparations are costly and place an unnecessarily large burden of proof on claimants or require proof of intentional disparate treatment, rather than disparate impact (Salim 2020). Therefore, scientists must establish trust with and assist communities, to empower them in pursuing meaningful reparations and interventions and helping alleviate the responsibility to create empirical evidence of harm. Additionally, the community-based participatory research methods employed seek to oppose the settler-colonial knowledge economy that exists within academia, by valuing cultural and experiential knowledge with mainstream scientific knowledge and aiming to avoid the exploitation of stories of pain in environmental degradation (Tuck and Wayne 2014).

Study location

In the San Francisco Bay Area, Hunter's Point, West Oakland, and Richmond are locations of major historic and present attention for environmental justice, within these areas are shipyards with radioactive contamination, the 880 and 580 freeways, the Port of Oakland, and Chevron refinery. Parts of these regions have been identified as SB 535 communities in CalEnviroScreen (OEHHA 2020 b). SB 535, a bill passed in 2012, which imposed that 25% of proceeds from funds generated by California's cap-and-trade program must go to projects to benefit disadvantaged communities (OEHHA 2020 b). These communities were defined as the highest 25% scoring census tracts based on areas disproportionately affected by environmental hazards, with rates of lower income, higher unemployment, lower home ownership, high rent burden, higher sensitivity, or lower education attainment (Rodriquez 2017). Although this analysis examines the larger San Francisco Bay Area, there is a specific focus on these vulnerable areas, as the interviews conducted are only with Richmond residents to examine community narratives and knowledge in a high-risk region.

Richmond has nearly double the prevalence of asthma in comparison to the statewide rates of asthma attacks (Collaborative Learning for Equity and Respiratory Health Lab 2020 a). Research on environmental contaminants in these areas must include meaningful community engagement to inform policy changes. Although there were limitations as to the level of community partnership which was possible through this study, the Richmond Environmental and Asthma Community Health Study at the University of California, San Francisco, through which this study recruits its participants, works with Lifelong Medical Care and the University of California, Berkeley to foster long-term community partnerships and engagement with youth with asthma. This UCSF study engages the enrolled youth through activities in a Youth Participatory Action Research program (YPAR), such as a summer internship program, an art mural and other community-focused benefits (Collaborative Learning for Equity and Respiratory Health Lab 2020 b).

METHODS

Air pollutant concentrations

To visualize long term air quality trends and investigate their relationship to sociodemographic data and asthma incidences, I used 69 nodes from the Berkeley Environmental Air quality and CO_2 Network (BEACO2N) in the San Francisco Bay (Figure 1). For each node, I downloaded data from 2016 through 2019 on aerosols and CO_2 concentrations from the BEACO_2N website (BEACO_2N 2020). I processed data in RStudio using R (RStudio Team 2020, R Core Team 2020). To calculate aggregated seasonal averages, I used the libraries of functions within the tidyverse, dplyr, and lubridate packages (Wickham et al. 2019, Wickham et al. 2018, Wickham and Grolemund 2011). I selected data that underwent the calibration method described by Shusterman et al., removing data that could not pass this initial quality control (Shusterman et al. 2016). Although extreme air pollution events are important to asthma, resulting acute spikes in emergency room visits due to asthma would not be represented in the available asthma data aggregated over several years. Thus, aerosol data above 50 micrograms per cubic meter was removed, to better visualize long-term, ambient differences by locations. I then calculated seasonal averages at each node. I gathered data from March 20th to June 20th for spring, June 20th for September 22nd for summer, September 22nd to December 21st for fall, and December 21st to March 20th for each year. From 2016 to 2019, for both CO_2 and aerosol concentrations, I aggregated the annual seasonal averages by averaging the four years together per season. The data was aggregated in this way to align with the available data on emergency room visits due to asthma in children from 2016 to 2018, while capturing more reliable data from later in the BEACO_2N network's development in 2019. I imported these aggregated seasonal averages for each node into ArcMap (ESRI 2020). To create visualizations for each season among CO_2 and aerosol concentrations, I used the IDW (inverse distance weighted) tool, with respect to a maximum of 15 neighbors and a minimum of 10 neighbors, at a power of 5 and a resolution of 5 kilometers. To derive mean values for each census tract for CO_2 and aerosol concentrations based on the interpolation, I used the GA Layer to Grid, Zonal Statistics as Table and Table to Excel tools.

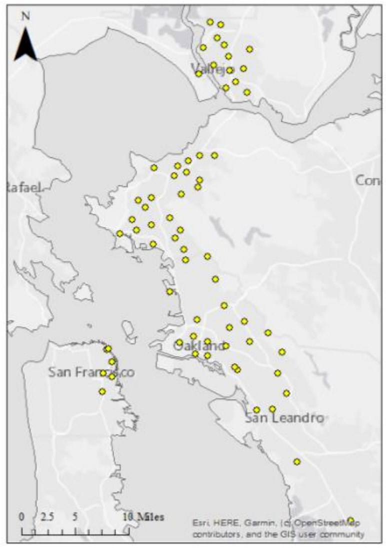

Figure 1. Map of BEACO$_2$N network in the San Francisco Bay Area with dots representing node locations included in this study.

Sociodemographic data

To inquire how sociodemographic data relates to census tract level air pollutant concentrations and asthma incidences in children, I created maps of tract-level percentiles of Black populations, Latinx populations, and non-Hispanic white populations in ArcMap using race, ethnicity, and population data from 2014 (California Department of Public Health Geospatial Resources 2018). Then, I downloaded shapefiles of median household income data from 2019, and census and zip code boundaries from the California State Geoportal (California Public Utilities Commission 2020 a, California Public Utilities Commission 2020 b). From these shapefiles, I created a map of tract-level median household income for the Bay Area in ArcMap.

Asthma incidences

Next, to spatially analyze asthma incidences in children and their relation to air pollutant concentrations and sociodemographic data, I obtained data of the number of ER visits and admissions from 2016 to 2018, with ICM-10-CM as the principal diagnosis code J45.xx for patients under the age of 18 years old from the California Office of Statewide Health Planning and Development (OSHPD 2020). This data included patient zip codes in Alameda, Contra Costa, San Francisco, Solano, Marin, Napa, San Mateo, Santa Clara, and Sonoma County. To estimate the asthma incidences in minors at the census tract level from the zip code level, I used total population numbers from the race, ethnicity, and population shapefile and CalEnviroScreen 3.0 data (OEHHA 2018). To obtain an estimated number of aggregated asthma incidences at the census tract level in R, I divided aggregated asthma incidences from the zip code data by the total population at the zip code level and multiplied by the total population of minors (under the age of 18) in census tracts within a zip code (RStudio Team 2020, R Core Team 2020).

Spatial statistical analysis

To statistically explore the relationship among CO_2 concentrations, aerosol concentrations, race/ethnicity percentiles, median household income, and asthma incidences, I utilized Spearman correlations and linear regression models in R, as the majority of the data was not normally distributed. I created boxplots to visualize each aggregated seasonal average and range. Afterwards, I ran linear regression models between each individual variable – estimated aggregated asthma incidences, percentiles of Black populations, percentiles of Latinx populations, percentiles of non-Hispanic white populations, median household income, aggregated seasonal averages of CO_2, and aggregated seasonal averages of aerosols per census tract. I reported the slope of the linear model, the p-value of the t-test, their significance code, adjusted r-squared, and correlations.

Semi-structured interviews

Following the secondary data analysis, I conducted 20 semi-structured interviews with families with children affected by asthma with monetary compensation, to gain anecdotal narratives of perspectives on youth asthma, environmental health, and participation in research. I recruited interview subjects, either parental guardians or children 14 years old and above, through Neeta Thakur and Alma Andrade with UCSF, via their current Richmond Environmental and Asthma Community Health (REACH) study (Collaborative Learning for Equity and Respiratory Health Lab 2020 a). We advertised the opportunity to eligible subjects, and then they reached out via telephone or email if they were interested. Prior to beginning the interviews, I confirmed consent and/or assent with the participant. I conducted interviews over the phone through Zoom.

Seven participants were interviewed due to time limitations. Four of participants had participated in the YPAR program, and three had not participated in the YPAR program, but were participants in the REACH study. The interviews investigated the experiences of youth with asthma, asthma exacerbations, their perception of environmental justice, and their perception of community needs. To highlight patterns around these topics, I statistically analyzed summary results describing the frequency of certain responses and feelings in MAXQDA (VERBI Software 2019).

RESULTS

Air pollutant concentrations

For CO_2 and aerosols, each aggregated season was not significantly different from one another across the four seasons (Figure 2). For CO_2, the aggregated seasonal averages had the highest median concentration in the fall, then the winter, spring, and lastly summer. For aerosols, the highest median concentration was in the spring. However, when interpolated and visualized in ArcMap, the seasonal averages reflected a different pattern. For CO_2, the winter averages appeared to have a larger spread of higher concentrations than in other seasons (Figure 2). I found consistently higher concentrations of CO_2 in the north of Richmond around San Pablo and in West Oakland (Figures 3). For aerosols, I found a similar pattern in these regions in the visualization map. Despite the highest median aerosol concentrations in the spring shown by the boxplot, the interpolated map showed overall higher concentrations in the fall and winter averages (Figure 4). I found consistently higher concentrations of aerosols in lower West Oakland, Alameda Island, and slightly North of Richmond around San Pablo (Figures 4). I identified lower concentrations of both CO_2 and aerosols consistently around Berkeley, El Cerrito, Montclair and eastern Contra Costa County (Figures 3 and 4).

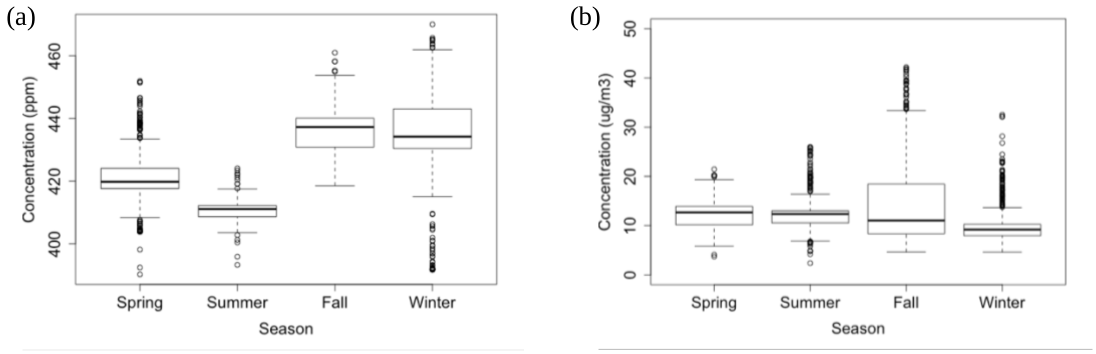

Figure 2. Boxplot of the aggregated seasonal averages for 2016 to 2019 of CO_2 concentrations in parts per million (a) and boxplot of the aggregated seasonal averages for 2016 to 2019 of aerosol concentrations in micrograms per cubic meter (b).

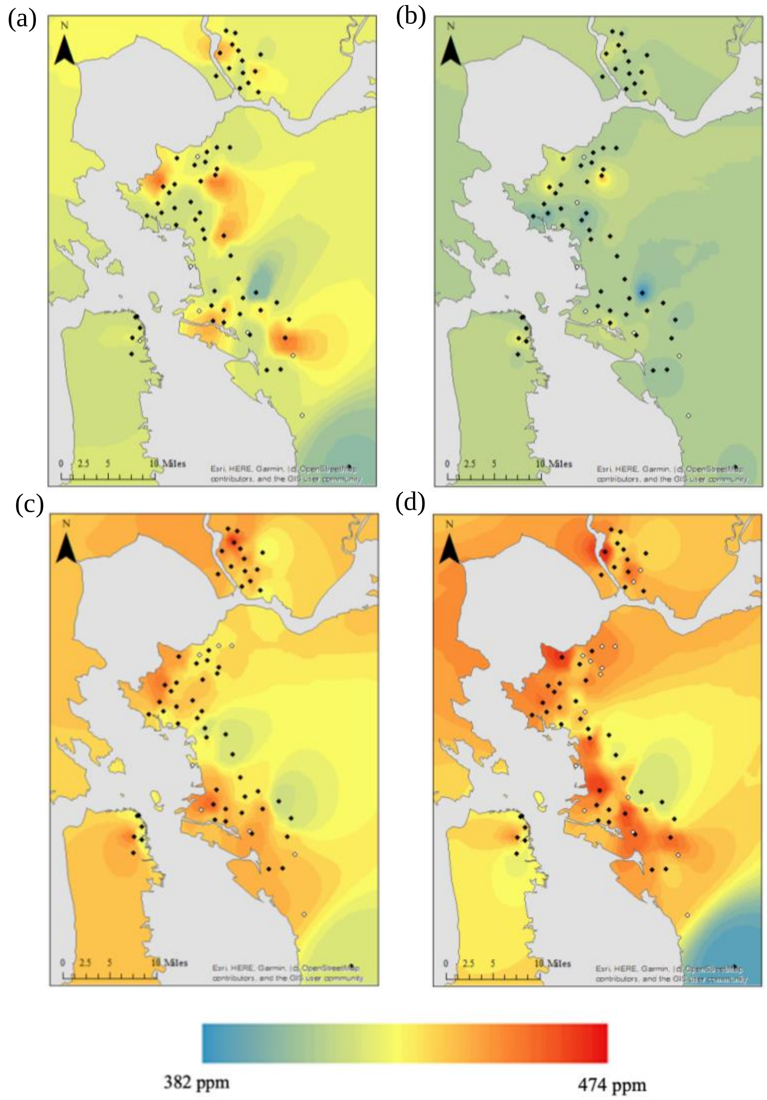

Figure 3. Interpolated aggregated seasonal averages of CO_2 concentrations for spring (a), summer (b), fall (c), and winter (d). Scale in parts per million for CO_2 shown below maps. Points show the BEACO$_2$N nodes. Points in black represent sensors with data, while points in white represent sensors that were missing data.

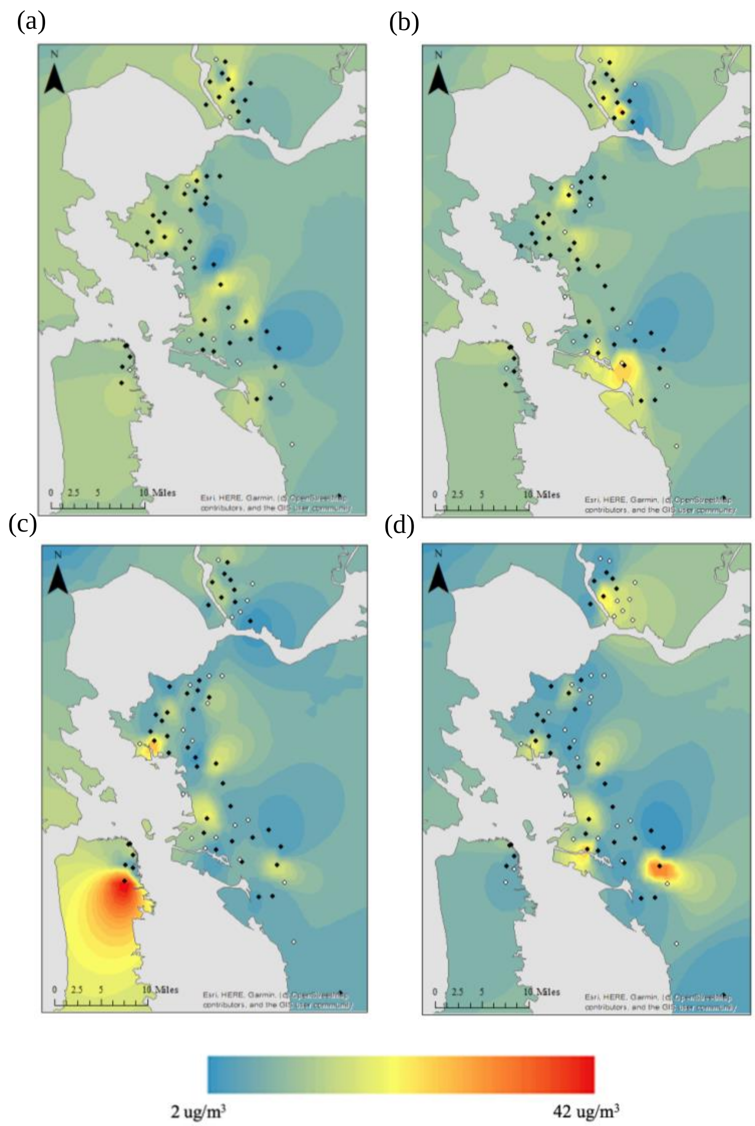

Figure 4. Interpolated aggregated seasonal averages of aerosol or particulate matter (PM) concentrations for spring (a), summer (b), fall (c), and winter (d). Scale in micrograms per cubic meter shown below maps. Points show the BEACO$_2$N nodes. Points in black represent sensors with data, while points in white represent sensors that were missing data for the given aggregated seasonal period.

Sociodemographic data

The maps visually indicate high percentages of white populations in eastern Contra Costa County, North and central San Francisco, Marin, Mill Valley, around the Oakland Harbor, and Point Richmond (Figure 5). I found high percentages of Latinx populations in the Mission District of San Francisco, South San Francisco, central Richmond, San Pablo, Southeast Oakland, San Leandro, San Rafael, and San Quentin (Figure 5). The maps showed high percentages of Black populations in Hunter's Point, West Oakland, San Leandro, South Richmond, and San Pablo (Figure 5).

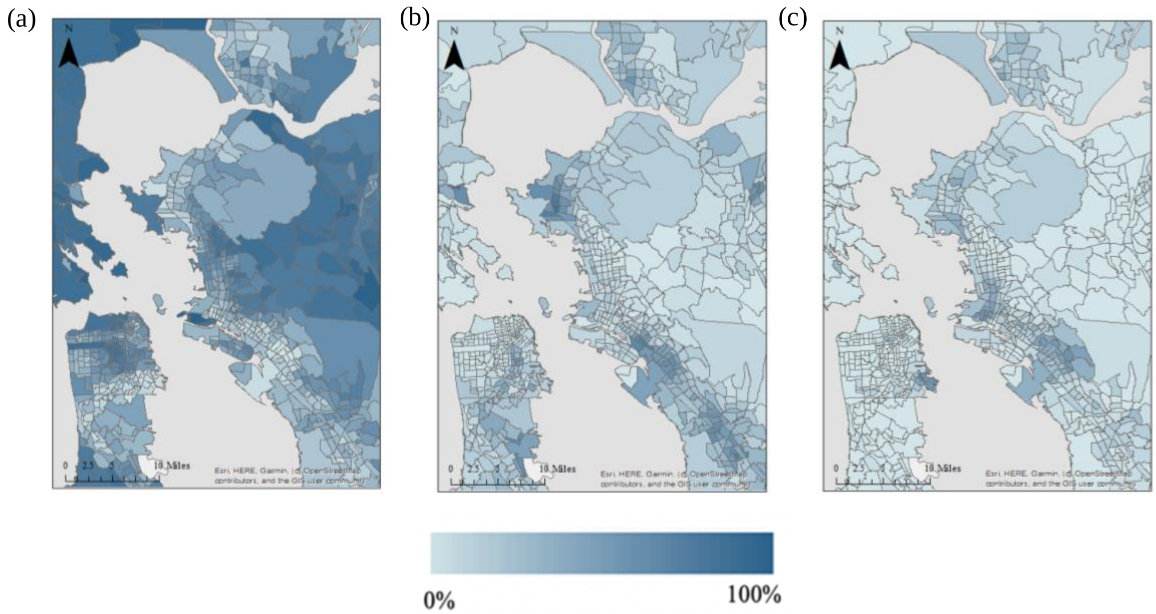

Figure 5. Demographic percentiles from 2014 in the San Francisco Bay Area for non-Latinx white populations (a), Latinx populations (b), and Black populations (c).

Median household income data from 2019 showed patterns of lower median household incomes in areas of West Oakland, Richmond, Hunter's Point, San Leandro, and Hayward (Figure 6). Patterns were in proximity to highways and were similar to regional patterns of environmental disparities and health outcomes (Figure 6). The maps showed very low median household incomes near universities and airports, such as the University of California, Berkeley, the College of San Mateo, San Francisco State University, and the San Francisco International Airport.

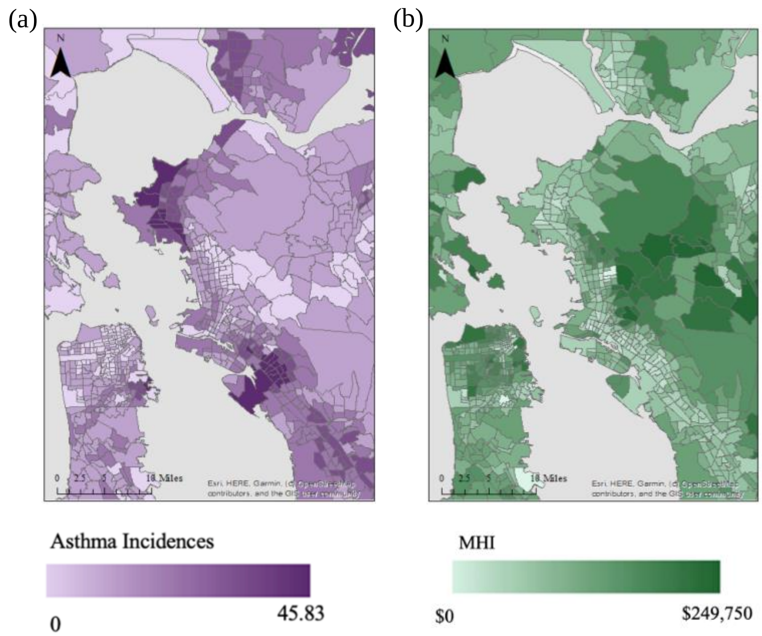

Figure 6. Emergency room visits due to asthma among children under 18 years old aggregated from 2016 to 2018 (a) and median household income from 2019 in the San Francisco Bay Area by census tract (b).

Asthma incidences

Aggregated ER visits due to asthma in minors from 2016 to 2018 reflected higher incidences occurring in West Oakland, Hunter's Point, Richmond, San Pablo, Southeast Oakland, North San Leandro, Hayward, and North Concord (Figure 6). The maximum value re-estimated at the census tract level was 45.83 visits. I identified lower incidences in Contra Costa County and Brisbane.

Spatial statistical analysis

Air pollutant concentrations and sociodemographic data

The linear regression models between median household income and aggregated seasonal air pollutant concentrations, for both CO_2 and aerosols, showed negative relationships (or slopes), except for potential outliers in the CO_2 summer concentrations and aerosol fall concentrations which had a positive relationship (Table A1 and A2). Correlations between seasonal air pollutant concentrations and income across all census tracts were found to be negative, except for with CO_2

summer concentrations and aerosol spring, summer, and winter concentrations (Table A1 and A2). Although the linear regression model slope of aerosol concentrations and median household income for spring and winter was negative, the correlation was slightly positive (Table A2). For CO_2 and aerosols, each season had a statistically significant p-value of the t-test in relation to income, apart from the spring season for aerosols ($p < 0.05$; Table A1 and A2).

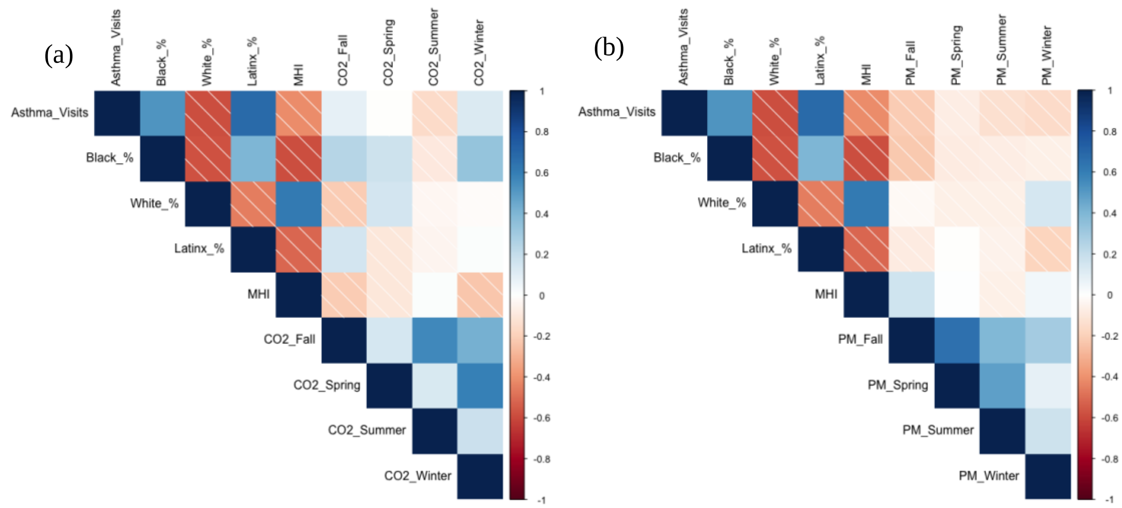

Figure 7. Spearman correlations among variables (emergency room visits due to asthma, race/ethnicity percentiles, and median household income, with aggregated seasonal CO_2 concentrations (a) and aggregated seasonal aerosol concentrations (b).

Percentages of white populations had slightly negative relationships and slightly negative correlations with the aggregated seasonal average air pollutant concentrations for both CO_2 and aerosols. However, in the spring for CO_2, the slope and correlation were slightly positive, and in the winter for CO_2, the slope was slightly positive (Table A3 and A4). These relationships were statistically significant in spring, summer, and fall for CO_2 and in the summer and fall for aerosols ($p < 0.05$; Table A3 and A4). For percentages of Latinx populations and aggregated seasonal average air pollutant concentrations, the slope of the relationship and the correlations were mostly slightly negative, except in the fall for CO_2 and aerosols (Table A5 and A6). These relationships were generally less negative in comparison to non-Latinx white populations. The p-value of the t-test of the linear model was statistically significant in the spring and winter for CO_2 and in the spring, summer, and winter for aerosols ($p < 0.05$; Table A5 and A6). For percentages of Black populations and aggregated seasonal average air pollutant concentrations, I identified mostly positive relationships and correlations among CO_2 and aerosols, except for with summer CO_2 averages and spring and fall aerosol averages (Table A7 and A8). The relationship between percentages of Black populations and aggregated seasonal average air pollutant concentrations had statistically significant p-values for spring, summer, fall and winter CO_2 averages and aerosol fall and winter averages ($p < 0.05$; Table A7 and A8).

Air pollutant concentrations and asthma incidences

In the linear regression model and correlation tests across all census tracts, I found a small positive relationship and small positive correlation in between emergency room visits due to asthma in minors and aggregated seasonal concentrations of CO_2 for the fall and winter ($p < 0.05$; Table B1). CO_2 concentrations in the spring had a small positive relationship, yet a very slightly negative correlation (Table B1). Contrastingly, there was a slightly negative relationship and slightly negative correlation for the summer ($p > 0.05$; Table B1). For aggregated seasonal concentrations of aerosols, I found a small positive relationship for the summer and winter, but a small negative relationship for the spring and fall ($p < 0.05$ for spring, fall, and winter; Table B2). I found that aerosol concentrations across all seasons had a small negative correlation to emergency room visits due to asthma (Table B2).

Sociodemographic data and asthma incidences

Sociodemographic data and asthma incidences generally showed strong statistical relationships, in patterns that reflected that census tracts with lower median household incomes and higher percentiles of marginalized racial or ethnic groups were more positively linearly related and correlated to higher emergency room visits due to asthma in children. Emergency room visits due to asthma in minors and racial/ethnic demographics had consistently very statistically significant p-values of the t-test in a linear regression model (Table C1). For percentages of non-Latinx white populations, this relationship and the variables' correlation was negative ($p < 0.05$; Table C1). For percentages of Latinx communities, this relation and correlation was positive and the strongest ($p < 0.05$; Table C1). For percentages of Black communities, a positive relationship and correlation existed between asthma incidences in children ($p < 0.05$; Table C1). Income and asthma incidences across census tracts had a very large negative relationship and negative correlation ($p < 0.05$; Table C2). The linear regression between income and these three racial or ethnic demographics were all equally statistically significant, with percentages of white populations having a small positive relationship and correlation, percentages of Latinx populations having a small negative relationship and correlation, and percentages of Black populations having a small negative relationship and correlation ($p < 0.05$; Table C3). Income and Latinx percentiles had a slightly steeper negative slope than with Black percentiles (Table C3).

Semi-structured interviews

Interviews with youth with asthma enrolled in the REACH study reflected that one's sense of control over their asthma triggers and symptoms were impacted by their experience with being involved in environmental health research. Youth involved in the YPAR program overall mentioned more specific sources of environmental pollution and involvement in more community engagement than those that did not participate in the YPAR program. 57% of the participants attended school within Richmond, 29% in Pinole, and 14% in El Cerrito. 71% reported having a family member with asthma. 43% reported daily usage of an inhaler, while 14% used an inhaler monthly, 29% carried an emergency inhaler with them, and 14% no longer used their inhaler. 14% reported feeling limited to their daily activities. On a scale of one to ten of increasing severity of asthma, the average rating reported was 2.5. All participants said that their asthma had improved with age or because of better treatment and management. 86% of participants felt limited to physical exercise and running. 86% mentioned pollen or pet allergies as an asthma trigger, 71% mentioned smoke, and 71% mentioned dust. 57% mentioned some type of pollution being a trigger for their asthma. All but one of these participants mentioning pollution had engaged in the YPAR program. 43% of participants referenced the Chevron refinery in their concerns about environmental triggers for asthma in their community (all but one being YPAR participants), with another 14% mentioning more vaguely factories in Richmond (a YPAR participant). 29% described noticing a beneficial difference in air quality and their breathing in parks and green spaces, while 14% described parks as a trigger because of allergens. 57% of participants were familiar with the concept of environmental justice and felt that it was relevant to their community, with all but one being YPAR participants. All participants said participating in the REACH study, regardless of if they were in YPAR, benefitted their understanding of environmental health factors that may impact their asthma. They also all said that this increased knowledge helped them in turn feel more in control of their asthma. Non-YPAR participants expressed benefitting from communicating with doctors about triggers and management and gaining a general knowledge or awareness of the scope and seriousness of the issue. One participant expressed that they started doing breathing exercises at home every day after being involved in YPAR and REACH. YPAR students described more detailed benefits of learning about how home ownership, income, redlining, and racism related to asthma. In particular, some YPAR participants discussed how learning of the history of the issue and the quantification of the impacts assisted their awareness of what precautions they can take, why they might have asthma, and the importance of caring for themselves. For example, a YPAR participant said, “I feel like, when I first thought of asthma, I sort of thought of it as a genetic thing, like oh you can't really breathe right, but over time, I started learning that there are environmental factors, mostly obviously man-made, that really really impact your asthma and wellbeing. Learning about the environment and what we're doing towards it has definitely expanded my knowledge how it impacts my asthma.” 29% of the total participants had also participated in other programs, such as the Earth Team and YES Nature to Neighborhoods, both of which were YPAR participants. Another YPAR participant described, “They [YES Nature to Neighborhoods] helped me realize it's not our fault we have all these health issues. It's the big corporations like Chevron that usually take the areas that are – I don't want to say bad – but best for them, and they don't really care how it impacts the environment, the people, the community, the animals, and anything in general.”

All participants expressed feeling some sort of negative emotion about their asthma and the overall issues of asthma and the environment in their community, described as feeling sadness, fear, disheartened, upset, vulnerable, insecure, or burdensome. For example, one participant said, “It's actually kind of sad. I feel like because I've lived in the Richmond/San Pablo area my whole life, and I've never left the Bay Area, it's statistically known that my asthma and health are going to be worse off than other people in California.” However, 43% of the participants (all but one of which were YPAR participants) said they also felt positively by learning that they were not alone or felt motivated or inspired to work towards changes in their community. A YPAR participant stated, “I did a lot of community advocacy with them [YES Nature to Neighborhoods], and they definitely made me fall in love with Richmond. I used to not really like it as much. I would always look at the negative aspects of it. They helped me realize that there's so many more positive aspects." Additionally, a non-YPAR participant said, "Knowing I'm not alone in this and that there are people who relate to me has helped me a lot."

86% of participants said they felt valued and advocated for in their community and local systems, but some said both yes and no, as 43% (two YPAR and one non-YPAR) said they did not feel valued because of a lack of proper recognition of their mental and physical wellness, a lack of proper access to information, and a lack of resources in the community, such as access to grocery stores and healthy food. Options. Those who answered yes and no said that people in the community were making positive efforts, but this support was lacking on a larger, systemic scale. In discussing what resources participants might need or what their suggestions would be to ease these burdens, 43% mentioned removing, moving, or proceeding with legal action against Chevron, all but one being YPAR participants. 71% of participants said they felt that there should be increased education or awareness on asthma as a public and environmental health issue, to de-stigmatize feelings of embarrassment about having asthma and so that people take asthma more seriously. All participants said they would like to be involved in community organizing and activism in the future, and 2 of the participants (both being YPAR participants) said they had already been involved in community or civic engagement around environmental health matters. Other interesting themes that were brought up across individuals included: government action, access to health insurance, access to more affordable medicine, the importance of self-care, food justice and accessibility, resources for higher education, plastic and trash pollution, the desire for increased involvement in activism from older generations, and the desire to learn more.

DISCUSSION

The results generally show the predicted trend of correlations between higher air pollution burdens, increased asthma incidences in minors, lower household incomes, and higher percentages of Latinx and Black populations (Figure 7). However, this relationship was not entirely consistent throughout the statistical tests. Although aerosols are more directly associated with asthma perturbations, CO_2 was found to have a more consistent relationship with asthma incidences than aerosols, due to limitations in the available data (Table B1 and B2, Tao 2016). Surprisingly, Latinx communities generally had a very slightly negative relationship with pollutants, despite having the largest positive relationship with emergency room visits due to asthma, suggesting that environmental health factors impacting asthma may be more complex across Latinx communities. (Table A5, A6 and C1, Juarez et al. 2018). Income also had a more largely negative relationship with emergency room visits due to asthma in children than race and ethnicity, as a lack of access to health care and management treatments may increase the likelihood of a severe asthma attack resulting in an emergency room visit, which was a concerned highlighted in interview responses as well (Jorgenson et al. 2021). Semi-structured interview responses from asthmatic youth ages 13 to 18 from the Richmond area overall reflected that participation in youth engagement programs impacted perceptions and increased awareness on environmental health and community engagement.

Sociodemographic data and air pollutant concentrations

The findings in this study that address the spatial distribution of air pollution burdens and who is most impacted suggest that median household income may have a stronger relation to air pollutant concentrations than race and ethnicity percentiles. Median household income had a mostly negative relationship with air pollutant concentrations, yet some seasonal averages had small negative slopes but slightly positive correlations. These differences may be explained by the suppressor effect, in which the correlations were so close to zero that the difference in the signs may be due to random variation around zero (Falk and Miller 1992). Race and ethnicity percentiles and air pollutant concentrations were also partially inconsistent and complex. Air pollutant concentrations mostly had a negative relationship with Latinx population percentiles, which is contrary to the hypothesized findings. This may perhaps be because Latinx populations consist of many white Latinx individuals, who may sometimes face less discriminatory systemic inequities due to colorism or lower linguistic isolation (Rubio and Grineski 2021). Since categorically analyzing environmental injustices related to race and ethnicity is very complex, as racial and ethnic groups are not homogenous, median household income (or income inequality) may be a stronger predictor of air pollution burdens and related health impacts (Jorgenson et al. 2021).

Air pollutant concentrations and asthma incidences

Although relationships between air pollutant concentrations and asthma incidences in children were mostly positive, there were inconsistencies among the slopes of the linear regressions and correlation tests. Two of four seasons for aerosol concentrations showed positive relationships, but all aerosol and asthma correlations were negative. This is most likely explained by the aforementioned suppressor effect and limitations in the aerosol data reliability (Falk and Miller 1992). The patterns among CO_2 and aerosol concentrations in this research can be used to estimate other pollutant species, such as carbon monoxide (CO) and nitrogen dioxide (NO_2). CO_2, CO, and NO_2 often come from similar sources, mainly the combustion of fossil fuels, thus relationships regarding CO_2 can be predictive of estimates for CO and NO_2, with variation in co-pollutants occurring among different industrial emissions sources (Tao 2016). Therefore, the CO_2 model in this study is also an indicator of other pollutant species which are more harmful to the respiratory system (Boyce and Pastor 2013).

In a previous study using 2012 U.S. Environmental Protection Agency (EPA) data on emissions and the Toxic Release Inventory, co-pollutant intensities were estimated based on mean CO_2 output, categorized by industry emissions (Boyce and Pastor 2013). Per industry, the highest co-pollutants were sulfur dioxide (SO_2) for power plants, petroleum refineries, primary metal manufacturers, chemical manufacturers, paper mills, and food manufacturers (Boyce and Pastor 2013). NO_x was the highest estimated co-pollutant for nonmetallic mineral product manufacturers, and Risk-Screening Environmental Indicator chemicals were the highest estimated co-pollutant for transportation equipment manufacturers (Boyce and Pastor 2013). This information is particularly relevant to the Richmond and West Oakland area, near the Chevron oil refinery and surrounding manufacturers, where higher CO_2 emissions are likely coupled to higher SO_2 and NO_x co-pollutants, which may provoke irritant-induced asthma in nearby residents (Andersson et al. 2006). Urban areas tend to be more impacted by both rhinitis and bronchial asthma than in rural areas (D’Amato 2011). Other research has also suggested that increases in atmospheric CO_2 concentrations may increase pollen production and exposure to allergenic pollens (Wayne et al. 2002). Air pollutants may modify their antigenic properties and adhere to pollen, promote airway sensitization, and increase allergic response (D’Amato 2011). Although limitations in the air pollutant data caused some shortcomings of the statistical results, the visualizations affirm that certain regions are more impacted by various types of air pollution, environmental injustices and related respiratory impacts, despite the impact of air pollution on emergency room visits due to asthma being complex and varying across seasons.

Sociodemographic data and asthma incidences

Median household income and asthma incidences in children had the strongest negative slope, while race and ethnicity percentiles supported the predicted relationships with asthma incidences in children with the strongest correlations. Income and asthma having the strongest negative relationship and slopes across all variables affirms previous research which found that income inequality worsened the relationship of air pollution and life expectancy globally (Jorgenson et al. 2021). Latinx population percentiles had the strongest negative slope with median household income, yet Black population percentiles and median household income had a stronger negative correlation. White population percentiles had a negative relationship and the strongest slope with asthma incidences, while Latinx population percentiles had the strongest (positive) correlation. Language may be a significant environmental justice variable and allude to this complexity among Latinx population percentiles being more strongly associated to asthma incidences in children, but less strongly associated to air pollutant concentrations than Black population percentiles. Asthma incidences may possess a complex environmental justice relationship among Latinx communities, potentially due to related increased chronic health risks for Latinx communities or other health disparities impacted by housing, indoor and outdoor pollutant exposures, healthcare, workplace hazards, immigration or linguistic isolation (Juarez et al. 2018). Previous research has affirmed that non-English speaking homes were found to be more significantly exposed to vehicular hazardous air pollutants than in English speaking homes in white, Asian, and Latinx children (Rubio and Grineski 2021). The sociodemographic data and asthma incidences showing the strongest slopes and correlations reflects the strong effect and impact of this environmental justice issue, although the direct causation by air pollution exposures remains much more complex.

Semi-structured interviews

Interviews conducted with asthmatic youth from the Richmond area suggest that youth participatory action research programs empower youth to feel a sense of belonging in their community, to possess a less stigmatized view of their asthma, and to understand that who most often suffers from asthma is a systemic environmental justice issue. Students engaged in the youth participatory action program (YPAR) seemed to have developed a more expansive idea of environmental health and its connection to their own neighborhoods. However, this may also be due to having a greater level of comfortability in a research and interview setting. The YPAR participants expressed having a greater sense of community belonging and empowerment; for some, the program seemed to be a formative experience of their development of their interests while in high school. Many non-YPAR students often thought of their experience as a study participant in REACH as youth engagement in research. A very similar study conducted with the RYSE Center in Richmond found that youth responded with increased feelings of empowerment and increased interests in civic engagement after engaging in an environmental justice research study pertaining to their community (Nolan et al. 2021). Many YPAR students possessed a strong interest or passion for the environment; some placed importance on how their individual actions impacted the environment. While these individual actions may help one feel in control of bettering their environment, it may place an improper, stressful responsibility on the civilian or consumer, failing to acknowledge proper corporate and systemic responsibility. Perhaps future YPAR programs could incorporate more radical environmental justice and public health ideas of capitalist extractivism, mutual aid, and research justice. Some youth had also participated in other programs or organizing, such as the Earth Team or YES Nature to Neighborhoods. Another similar mixed methods study in the Excelsior district of San Francisco described I-280 as a “color line,” with dynamics of opposite sides of the freeway being very different, with greater bilingual and immigrant populations and higher emergency room visits due to asthma compared to the rest of San Francisco (Wier et al. 2009). This study emphasized similar community concerns through surveys around impacts of transportation, access to health care, and safety and health in proximity to schools (Wier et al. 2009). Qualitative investigations with youth help emphasize the intersectional impacts of environmental disparities and health inequities which pertain to many of the participants spoken with in this study, as many participants were from non-English speaking homes (Rubio and Grineski 2021). Community-based participatory methods, especially those that engage youth or multiple generations of a community, such as in this study, are crucial to the development of environmental justice research and policy to address research justice, social determinants of health, and cumulative environmental health issues.

Synthesis of results

The qualitative results from the interviews with asthmatic youth speak to many of the spatial hot spot areas of air pollution and health and social disparities in the San Francisco Bay Area, particularly for Richmond. Income and race and ethnicity seem to have stronger associations to asthma incidences in children than air pollution alone, due to both systemic social determinants of health and complexities and limitations of air pollution modeling. Involving community members, especially youth, is crucial to making progress on environmental justice issues and empowering youth to manage their asthma and understand these systemic health disparities. Experiential and cultural knowledge must be integrated into environmental assessments, as research and policy seek to address the cumulative impacts of environmental stressors using multi-pollutant frameworks (Smith and Laribi 2021).

Overall environmental burden results from CalEnviroScreen 3.0 show similar patterns with the highest scores (91-100%) in San Pablo, South Richmond, East Oakland, and Hunter's Point, and almost as high (~ 81-90%) in West Oakland and South San Francisco (OEHHA 2018). However, the CalEnviroScreen $PM_{2.5}$ indicator map does not align as well with the visualizations and findings in this study. The indicator map of diesel PM reflects more similar patterns in this study's model, with Oakland, central San Francisco, and inner Richmond being in the 90 to 100 percentiles (OEHHA 2018). However, more elevated diesel PM trends occurring throughout San Francisco is inconsistent with the aerosol findings in this study (OEHHA 2018). These differences may be due to the smaller network density of five monitors for $PM_{2.5}$, the CARB on-road emissions model, or differences over time in this data from 2012 to 2014. This study helps further quantify and update disparities in the Bay Area at a higher resolution, emphasizing the importance in the surrounding location of one's residence and a lack of consent involved in having to live in such proximity to environmental health hazards.

Limitations and future directions

Some limitations and inconsistencies in the findings may be due to various limitations in the data sources. Data at each node location in the BEACO$_2$N network was not all available at the same resolution across locations, as some sensors would have errors which invalidated several months of data per year. Greater inconsistencies, errors, and a greater range in the aerosol data specifically is most likely due to less reliability in the lower cost sensors used to measure aerosols, in comparison to the Vaisala CarboGap GMP343 non-dispersive infrared CO_2 sensors. The Shinyei PP42DNS sensors used in BEACO$_2$N most reliably measure low and medium concentrations of aerosols; therefore, higher concentrations of aerosols may not be as accurately captured (Austin et al. 2015). There also may be discrepancies on the aerosol measurement of the total amount of particulate matter in the air, versus solely measuring the typical lung irritant particulate matter sizes of 2.5 and 10 microns. Some complications in interpreting statistical results also arise from the division by seasons, aggregation of several years of data, and the simplified spatial modeling approach. However, seasonal trends in the air pollution may be explained by surface inversions, in which the sun heats the atmosphere more than the Earth's surface, causing short-term increases in pollutant concentrations, although emissions may remain consistent (Figure 6, Ning et al. 2018). Although this study uses a similar approach to CalEnviroScreen 3.0, using aggregated annual means and Kriging interpolation, the U.S. EPA recommends air pollution dispersion models such as CTDMPLUS (OEHHA 2018, EPA 2017). Additionally, some areas categorized as lower income census tracts may be explained by areas in which students reside that are not their primary residence as recorded in census data and areas with low population numbers in general, such as surrounding airports (Figure 6).

Future steps in this research may seek to incorporate CO concentration data and CO_2 emissions data from BEACO$_2$N that newly became available and highway traffic data. Additionally, I plan to conduct more semi-structured interviews with asthma youth from Richmond for a larger sample size and to compare interview responses to other data previously collected on the same participants in the UCSF Richmond Environmental and Asthma Community Health study. Data gathered in this study and through BEACO$_2$N can also be utilized to look at relationships across asthma and sociodemographic data within individual census tracts. This would especially be important to investigate near ports in the San Francisco Bay Area, as ports have been found to be associated with harmful environmental justice indicators and higher sociodemographic vulnerabilities in nearby residing communities (Greenberg 2021). Higher density air monitoring networks, greater uniformity and replicability in air pollution modeling, and higher resolution data is important for strengthening the reliability and reach of cumulative environmental justice assessments. Increased efforts to incorporate community-based participatory research and citizen science involving youth and multiple generations of a community are crucial to better address intersectional environmental and public health issues (King et al. 2021). Incorporating research justice approaches to science in educational systems in particular pose abundant opportunities for empowering, engaging solutions to addressing environmental health, mental health, preventative health, and health inequities. Health classes in education systems should also work to destigmatize health issues that youth may feel insecure about, especially those that disproportionately affect vulnerable groups, such as asthma. More initiatives for disadvantaged communities need to be taken to connect policy, research, and communities, and mixed method analyses of these factors should be regularly assessed to determine if policies and programs are effective.

Broader implications

This work weighs the benefits of different measurement and modeling strategies and updates information on risk assessment and health outcomes associated with air pollution for the Bay Area. Many environmental justice research and articles on the issue of air pollution and asthma were produced in the past few years, and research has shown regulations to be effective in decreasing $PM_{2.5}$ and NO_2 concentrations (Tao 2016). However, protections, education and partnership with vulnerable and marginalized communities must be increased further to address this persisting issue. This study highlights the salient factors that must be considered regarding how individuals operate in their environment and the local factors that affect their health. This work is relevant to the AB 617 bill, which prompted SB 535 identification and required the establishment of a program to measure community-scale pollutants and a statewide monitoring plan for air quality, which is still in development but will provide for future meaningful comparisons (OEHHA 2020). More initiatives for disadvantaged communities need to be taken to connect policy, research, and communities. Although there are many efforts to model and measure air pollutants, policy-based research must include a comprehensive investigation of the effects on low-income and minority communities (Smith and Laribi 2021). Only then can we fully understand the critical need for equitable policy that acknowledges and addresses these disparities, and work to increase access to green spaces, more strictly regulate distances of schools and residences from major freeways and roadways and increase home ownership among these disproportionately affected communities. Education, outreach, and community participation in policy must be made available to those living in areas with unequal environmental burdens.

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APPENDIX A: Air pollutant concentrations and sociodemographic data

Table A1. Statistical results from a linear regression model and correlation test between median household income and aggregated seasonal averages of CO_2 concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	CO_2 Spring	CO_2 Summer	CO_2 Fall	CO_2 Winter
Slope	-520.0	1048.7	-1125.5	-404.6
P-value	0.00736 **	0.0515 .	$1.40e^{-8}$ ***	$6.46e^{-5}$ ***
Adjusted R^2	0.008606	0.003898	0.04265	0.0207
Correlation	-0.1009065	0.01649501	-0.2171563	-0.1485418

Table A2. Statistical results from a linear regression model and correlation test between median household income and aggregated seasonal averages of aerosol concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	PM Spring	PM Summer	PM Fall	PM Winter
Slope	-839.8	-2277	668.4	-1115.3
P-value	0.164	$8.27e^{-7}$ ***	0.000267 ***	0.00643 **
Adjusted R^2	0.001308	0.03203	0.01703	0.008942
Correlation	0.006005212	-0.06631722	0.1621367	0.04253025

Table A3. Statistical results from a linear regression model and correlation test between percent non-Hispanic white populations and aggregated seasonal averages of CO_2 concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	CO_2 Spring	CO_2 Summer	CO_2 Fall	CO_2 Winter
Slope	0.2154	-0.6322	-0.6242	0.06064
P-value	0.0801 .	0.0638 .	$7.28e^{-7}$ ***	0.347
Adjusted R^2	0.00288	0.003399	0.03237	-0.0001597
Correlation	0.158143	-0.03994914	-0.2177017	-0.01612323

Table A4. Statistical results from a linear regression model and correlation test between percent non-Hispanic white populations and aggregated seasonal averages of aerosol concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	PM Spring	PM Summer	PM Fall	PM Winter
Slope	-0.6139	-1.0956	-0.2427	-0.2171
P-value	0.108	0.000192 ***	0.0372 *	0.403
Adjusted R^2	0.002205	0.01789	0.004659	-0.00042
Correlation	-0.05997134	-0.1387666	-0.02377369	-0.03122999

Table A5. Statistical results from a linear regression model and correlation test between percent Latinx populations and aggregated seasonal averages of CO_2 concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	CO_2 Spring	CO_2 Summer	CO_2 Fall	CO_2 Winter
Slope	-0.29506	-0.3213	0.12663	-0.12004
P-value	0.000237 ***	0.1503	0.128	0.00435 **
Adjusted R^2	0.01734	0.001495	0.001848	0.009919
Correlation	-0.101581	-0.05373749	0.1517223	-0.1063022

Table A6. Statistical results from a linear regression model and correlation test between percent Latinx populations and aggregated seasonal averages of aerosol concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	PM Spring	PM Summer	PM Fall	PM Winter
Slope	-0.04682	0.4019	-0.01135	-0.4070
P-value	0.0191 *	0.0372 *	0.882	0.0165 *
Adjusted R^2	0.006859	0.004663	-0.001366	0.006614
Correlation	-0.091527	0.0777917	-0.005554741	-0.08944129

Table A7. Statistical results from a linear regression model and correlation test between percent Black populations and aggregated averages of CO_2 concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	CO_2 Spring	CO_2 Summer	CO_2 Fall	CO_2 Winter
Slope	0.43183	-0.3243	0.44845	0.22477
P-value	$3.15e^{-13}$ ***	0.0523 .	$2.14e^{-13}$ ***	$4.35e^{-13}$ ***
Adjusted R^2	0.07024	0.003861	0.07124	0.06942
Correlation	0.1760275	-0.07246072	0.2430053	0.2659304

Table A8. Statistical results from a linear regression model and correlation test between percent Black populations and aggregated averages of aerosol concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	PM Spring	PM Summer	PM Fall	PM Winter
Slope	-0.06511	0.04373	-0.17288	1.2174
P-value	0.728	0.762	0.00241 **	$<2e^{-16}$ ***
Adjusted R^2	-0.001228	-0.001269	0.0114	0.1266
Correlation	-0.01298601	0.01130811	-0.1130654	0.3574542

APPENDIX B: Air pollutant concentrations and asthma incidences

Table B1. Statistical results from a linear regression model and correlation test between aggregated emergency room visits due to asthma in minors and aggregated seasonal averages of CO_2 concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	CO_2 Spring	CO_2 Summer	CO_2 Fall	CO_2 Winter
Slope	0.07804	-0.05261	0.12465	0.17910
P-value	0.09 .	0.0015 **	0.00515 **	0.0416 *
Adjusted R^2	0.002617	0.01262	0.009496	0.004397
Correlation	-0.008033144	-0.1533025	0.08701604	0.1263435

Table B2. Statistical results from a linear regression model and correlation test between aggregated emergency room visits due to asthma in minors and aggregated seasonal averages of aerosols concentrations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	PM Spring	PM Summer	PM Fall	PM Winter
Slope	-0.003184	0.05348	-0.16921	0.04940
P-value	0.83	0.00542 **	0.000479 ***	0.0235 *
Adjusted R^2	-0.001332	0.009418	0.01553	0.00567
Correlation	-0.07993759	-0.1327779	-0.2128997	-0.1586113

APPENDIX C: Sociodemographic data and asthma incidences

Table C1. Statistical results from a linear regression model and correlation test between aggregated emergency room visits due to asthma in minors and race/ethnicity – percent non-Latinx, white populations, percent Latinx populations, and percent Black populations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	White Populations	Latinx Populations	Black Populations
Slope	-2.1157	1.7562	0.98996
P-value	$< 2e^{-16}$ ***	$< 2e^{-16}$ ***	$< 2e^{-16}$ ***
Adjusted R^2	0.2702	0.4355	0.2464
Correlation	-0.5808108	0.6855147	0.5205586

Table C2. Statistical results from a linear regression model and correlation test between aggregated emergency room visits due to asthma in minors and median household income. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05 on a 95% confidence interval.

Statistic	
Slope	-2618.4
P-value	$< 2e^{-16}$ ***
Adjusted R^2	0.1655
Correlation	-0.4169846

Table C3. Statistical results from a linear regression model and correlation test between median household income and race/ethnicity: percent non-Latinx white populations, percent Latinx populations, and percent Black populations by census tract. Significance codes are listed for the p-values, with three stars representing a value in between 0 to 0.001, two stars representing a value between 0.001 and 0.01, one star representing a value between 0.01 and 0.05, and a period representing a value between 0.05 and 0.1 on a 95% confidence interval.

Statistic	White Populations	Latinx Populations	Black Populations
Slope	$3.809e^{-4}$	$-1.940e^{-4}$	$-1.495e^{-4}$
P-value	$< 2e^{-16}$ ***	$< 2e^{-16}$ ***	$< 2e^{-16}$ ***
Adjusted R^2	0.3607	0.2178	0.2311
Correlation	0.6106663	-0.5143855	-0.5819843