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Prachi Prasad 04/17/2023

Warehouse & Commerce-Associated Air Pollution in Chicago and California; an Environmental Justice Issue

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2017

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An abstract of
a thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
in partial fulfillment of the requirements for the degree of
Master of Public Health in Global Environmental Health
2023

Abstract

Introduction: The World Health Organization cites air pollution as one of the world's largest single environmental health risk factors (WHO, n.d.). Significant economic growth over the past few decades has led to increased demand for products in parallel with the expansion of warehousing, commerce, and distribution industries and associated PM2.5 and NO2 pollution. These industries are most often located in communities that have been historically marginalized like cities in Southern California and parts of Chicago. With this increase in distribution, we aim to understand if there is an association between PM2.5 and NO2 pollution and warehousing activity from 2010-2020 in Southern California and Chicago.

Methods: This study used remote-sensing methodology including, random forest calibration to improve PM2.5 and NO2 NASA satellite data based on ground observations. Analysis of warehousing activity and population demographics against air pollution data was conducted using Linear Regression Modelling at an annual level from 2010-2020.

Results: In Southern California, PM2.5 and NO2 air pollution is significantly associated with increased warehousing activity and with communities with increased poverty, reduced education levels, increased traffic exposure and increased pollution burden. In Chicago, NO2 air pollution is significantly associated with warehousing activity and with communities with increased poverty, increased minority composition and traffic. PM2.5 levels in Chicago were only significantly associated with communities with high percentages of minority peoples.

Conclusion: Our findings suggest that increased warehousing activity measured by square footage and associated distribution mechanisms may contribute to increased levels of NO2 and PM2.5 in Southern California and NO2 levels in metropolitan Chicago. These warehouses are primarily in neighborhoods and communities that have been historically marginalized, making this an environmental justice issue.

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Acknowledgements

I would like to extend a huge thanks to my advisor, Dr. Yang Liu for all his help and guidance. I would like to sincerely thank Wenhao Wang, Yijing Zhu and Qingyang Zhu for their invaluable help and input. I would like to thank Sina Hasheminassab, Faraz Ahangar of AQMD and Dillon Bergin of MuckRock for their guidance and partnership. I am grateful for the NASA HAQAST Team for making this project possible. Finally, I am grateful to my friends and family for their love and encouragement.

Warehousing & Commerce-Associated Air Pollution in Southern California & Chicago; an Environmental Justice Issue

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Introduction

The World Health Organization cites air pollution as one of the world's largest single environmental health risk factors (WHO, n.d.). Chronic and acute exposure to pollutants like particulate matter has been associated with increases in hospital admissions and mortality due to respiratory and cardiovascular disease, and recent studies have linked these exposures with childhood asthma (Brunekreef, 2002). Previous studies have shown that PM2.5, PM 10, Black Carbon, and N02 are associated with emissions from warehousing, commerce, and traffic pollution (Shearston, 2020; Cohen, 2005).

PM 2.5 is a type of fine particulate matter that is released into the air as a result of various human activities, including transportation and industrial processes such as warehousing. NO2 is a type of nitrogen oxide that is released into the air as a result of various human activities, including transportation and industrial processes such as trucking and diesel activity. Studies have found a positive association between NO2 levels and proximity to major transportation corridors and areas with heavy truck traffic (Jerrett, 2010). A study conducted in the Los Angeles Basin region of Southern California found that NO2 levels were higher in areas with higher traffic volume and proximity to major transportation corridors (Marshall, 2018).

Significant economic growth over the past few decades has led to increased demand for products in parallel with the expansion of warehousing, commerce, and distribution industries. Global warehousing demand is projected to grow ~7% annually with $400 billion in value by 2025 (Ali, 2022). Warehousing activities have been associated with significant environmental externalities for local communities and the surrounding environment (Yuan, 2019). This study aims to look at the association between warehousing, commerce, and traffic pollution and PM 2.5

and NO_2 levels from 2010-2020 in the Inland Empire and Coachella Valley regions of California and around metropolitan Chicago.

Background

Industrial buildings contribute to roughly 30% of greenhouse gas emissions, including indirect emissions related to packaging waste production and increasing energy consumption (Malik, 2019; Rupp, 2022). These logistics activities increase industrial emissions and contribute to worsened environmental pollution with warehousing as a central step in the pipeline of logistical operations. The health effects of $PM_{2.5}$ have been well-documented in many studies involving premature death, asthma, heart disease, and respiratory illness (Davila Cordova, 2020; Tapia, 2020). Some studies have shown that acute exposure to PM 2.5 in addition to chronic exposure results in life-long effects like exacerbation of asthma in addition to short-term coughing and wheezing (Yuan, 2018b). Warehousing, commerce, and distribution are associated with significant emissions of PM 2.5 and N02 (Shearston, 2020). With the boom in consumer demand for fast production and shipping of products, companies like Amazon have capitalized on affordable land, zoned in low-income and minority neighborhoods. During the start of the pandemic, this demand increased exponentially with some of the greatest consequences resulting in Los Angeles and San Bernardino counties in California, and Chicago in Illinois. Systemic inequalities have positioned low-income and minority communities near industrial sites, warehousing, and distribution pathways (Maantay, 2000). Studies have shown that warehouses are disproportionately located within minority neighborhoods of low- and middle-income communities (Yuan, 2018b). These findings still hold while controlling for access to transport, population density, retail, wholesale industry, median household rent, and employment density in manufacturing (Yuan, 2018b).

Though this is a growing field of study, the exponential growth of warehousing in the past decade has not been well characterized compared with air pollution metrics. In addition, it is imperative that these findings be communicated to the citizens most at risk and used to inform policy and regulation of large corporations. This paper contributes to a growing body of literature on the impacts of warehousing and commerce on air pollution, and through its longitudinal analysis aims to highlight the massive impact of this environmental justice issue.

Southern California

The expansion in distribution, shipping, and airport thoroughfares is especially pronounced in the counties of Los Angeles and San Bernardino. In the 1990s, the growth of e-commerce and just-in-time delivery systems had a significant impact on warehousing and commerce activities in Southern California. The rise of online shopping led to a surge in demand for warehouse and distribution space, particularly in the Inland Empire region of the state. The 2000s and 2010s saw continued growth in warehousing and commerce activities in Southern California, with the region's logistics industry becoming increasingly sophisticated and specialized. The rise of automation and robotics in the industry has led to greater efficiency and productivity, and Southern California has become a hub for logistics technology companies. According to a report by the Los Angeles County Economic Development Corporation, the total volume of freight moving through Southern California in 2015 was 598.3 million, valued at $1.7 trillion (LACEDC, 2019). The region has been a leader in developing sustainable logistics practices, with efforts such as the Clean Air Action Plan and the Sustainable Freight Action Plan aimed at reducing emissions from trucks and other logistics vehicles.

In Los Angeles, the average size of warehouses built between 2007 and 2017 is 140,000 square feet compared to <70,000 square feet of those built before 2007 (Yuan, 2018b). Large companies like Amazon, UPS, and Walmart have profited off the low cost of land and location without considering the serious impacts on local communities. Across California, industrial vacancy rates have been decreasing over time, corresponding to an increasing leasing rate (LAEDC, 2019). According to the LAEDC Institute for Applied Economics, 20.8 million square feet of Industrial Space was constructed, with another 16.7 million square feet still under construction in 2015 (LAEDC, 2019). Amazon, which has a significant presence in the region with several large warehouses and distribution centers has faced criticism and protests from workers and activists over issues such as low wages, poor working conditions, and anti-union practices (Hernandez, 2021). On the government side, the South Coast Air Quality Management District (SCAQMD) is one of the major regulatory bodies overseeing environmental and public health issues related to logistics and warehousing activities in the Inland Empire. The agency has implemented various programs and regulations aimed at reducing emissions from trucks and other logistics vehicles, such as the Carl Moyer Program and the Goods Movement Program (SCAQMD, n.d.). The agency has also worked with industry stakeholders to develop voluntary programs aimed at reducing emissions and improving air quality, such as the Sustainable Freight Partnership (SCAQMD, 2020).

Environmental justice is a critical issue in the inland empire of California, particularly concerning warehousing activity. Southern California's warehousing and commerce activities have faced challenges related to environmental sustainability and labor issues. In 2015, the average annual wage earned by trade and logistics workers was $63,130 (LAEDC, 2019). Organizations like the Warehouse Worker Resource Center have been founded to improve working conditions in the warehouse industry in Southern California (WWRC, n.d.).

Metropolitan Chicago

Similarly in Chicago, communities are increasingly vulnerable to the impacts of diesel trucking through any of the five major intermodal hubs throughout the city. As cited in the 2020 City of Chicago Air Quality and Health Report, the Clean Air Act and local efforts have led to improvements in overall air quality (City of Chicago, 2020). Additionally, Cook County does meet current federal standards for pollutants like PM 2.5, and levels have decreased by around 40% since 2000 (City of Chicago, 2020). Through analysis of public records, it has been shown that vulnerable communities of low socioeconomic status are significantly more vulnerable to the impacts of air pollution (City of Chicago, 2020). Historically, segregation and systemic racism have positioned Black and Latinx peoples to have reduced access to quality healthcare and live in polluted areas of the city (City of Chicago, 2020). This study found that the South and West Sides of the city are the most vulnerable, with communities living near major highways and high concentrations of industry the most affected.

Aims

This project, through the NASA Health and Air Quality Applied Sciences Team (HAQAST), functions to use NASA data and tools to understand the impacts of air quality and trends globally in partnership with public health and international air quality agencies. This project is being conducted in partnership with the South Coast Air Quality Monitoring District (SCAQMD) of California whose mission is to improve air quality within the south coast air basin through community programs, business programs, and initiatives with local government. Additionally, the Chicago arm of the project is being completed in partnership with MuckRock News.

The primary aim of this thesis is to investigate the association between the growth of warehousing and distribution activities in the South Coast Air Basin of California and metropolitan Chicago and PM2.5 and N02 levels from 2010 to 2020 using satellite and ground measurements. **I hypothesize that increased warehousing activity during the latter half of the decade in combination with increased emissions from diesel-powered vehicles and other distribution mechanisms will be associated with increased PM2.5 and N02 levels in vulnerable communities.**

A secondary aim will be to explore the interactions of socioeconomic factors and demographics on populations who are vulnerable to air pollution within this region. I hypothesize that in consistency with historical trends, low-income communities that have been historically oppressed are most impacted by proximity to major roadways, large warehousing sites, and air traffic. Finally, the tertiary aim of this project is to eventually share these findings with the communities most at risk through a partnership with SCAQMD at Community Town Halls and other appropriate settings.

Methods

Data Retrieval

Warehouse Geography. Distribution and size of warehouses were analyzed through a database collated by Costar Realty Information Inc (CoStar, n.d.). From the warehouse database, latitude, longitude, square footage, and year-built variables were obtained within the study domain from

1880-2022. Costar database data contains incomplete or missing values for ownership, specification of use, and status of use so these variables were excluded from further analysis. Databases were obtained for both California and Illinois and subsetted to the respective regional domain as seen in Figures 1a & 2a.

Satellite Data. Satellite-predicted data was obtained from NASA MODIS and MAIAC repositories. We collected annual PM 2.5 and NO2 data from 2010-2020 at a ~1 km spatial resolution. The California raw satellite data within the study domain contains ~65,000 observations over the study period with 6,3298-point locations for each domain per year. Data were obtained and subsetted to the respective regional domain. Satellite data was obtained and subsetted for both California and Illinois. The Illinois raw satellite data within the study domain contains ~9,000 observations over the study period.

Ground Observations Data. Ground sensor measurements were obtained from federal database sources for both Chicago and California. California ground data was sourced from the Air Quality and Meteorological Information Systems (AQMIS) historical database in partnership with the SCAQMD. Currently, SCAQMD has deployed sensors through the AB617 program throughout this domain and has shared this data in combination with historical air quality data from the Air Quality Meteorological Information System (AQMIS) from 2010-2020. AQMIS data is managed by the California Air Resources Board (Cal ARB) and contains hourly PM 2.5 and N02 data for ~30-40 sensors. PM2.5 and NO2 concentrations were averaged and downloaded at an hourly level from 2010-2020. To match ground observations with satellite-based surface NO2 and PM 2.5 estimates, mean annual NO2 and PM2.5 measurements by monitor were calculated for each monitor summarizing hourly values to an annual mean. Illinois ground observations were obtained from the Environmental Protection Agency (EPA), Outdoor Air Quality Data - Download Daily Data portal. PM 2.5 and NO2 data were downloaded at a daily level from 2010-2020 for the state of Illinois. Similarly, daily average PM2.5 and NO2 measurements were calculated by monitoring an annual mean level.

California EJ Screen. In order to assess demographics and traffic counts in the Inland Empire, the California EnviroScreen 3.0 (2018) and 4.0 (2020) were downloaded from the California Office of Environmental Health Hazard Assessment database as a data frame and geodatabase files. Within these datasets, the primary variables of interest are Traffic Impacts, Pollution Burden, Poverty Percentile, Unemployment Percentile, Education Percentile, and CES 3.0 & 4.0 scores (Cal EJ Screen, n.d.). The EnviroScreen 3.0 was solely chosen for study analysis as the EnviroScreen 4.0 contains data from the COVID-19 pandemic that is beyond the study time period. These variables are described as follows.

- ❖ CES 3.0 Score: CalEnviroScreen Score, Pollution score multiplied by Population Characteristics score. This score is composed of exposure indicators, environmental effects indicators, sensitive population indicators, and socioeconomic factor indicators.
- ❖ Traffic: Traffic density, in vehicle kilometers per hour per road length, within 150 meters of the census tract boundary.
- ❖ Pollution Burden: Average of percentiles from the Pollution Burden indicators (with a half weighting for the Environmental Effects indicators).
- ❖ Poverty Percentile: As a function of the percent of the population living below two times the federal poverty line.

- ❖ Education Percentile: As a function of education which is the percentage of the population over 25 with less than a high school education.
- ❖ Unemployment Percentile: As a function of unemployment which is a percent of the population over the age of 16 that is unemployed and eligible for the labor force.

Chicago EJScreen. In order to assess demographic variables and traffic, shape-file data from the United States EJScreen were obtained. EJScreen is an EPA, environmental justice mapping and screening tool that uses a nationally consistent dataset using publicly available data. Within this data frame, the following variables were chosen (EPA, n.d.).

- ❖ Minority Percentile: The percent of individuals in a block group who list their racial status as a race other than white alone and/or list their ethnicity as Hispanic or Latino. That is, all people other than non-Hispanic white-alone individuals. The word "alone" in this case indicates that the person is of a single race, not multiracial.
- ❖ Low-Income Percentile: Percent of individuals whose ratio of household income to the poverty level in the past 12 months was less than 2 (as a fraction of individuals for whom the ratio was determined).
- ❖ Traffic: Count of vehicles per day (average annual daily traffic) at major roads within 500 meters (or nearest one beyond 500 m), divided by distance in meters. Calculated from U.S. Department of Transportation National Transportation Atlas Database, Highway Performance Monitoring System.

Land Usage Data. Land usage variables were obtained from the National Land Cover Database within the United States Geological Survey. Variables include open water, developed open space, developed low intensity, developed medium intensity, developed high intensity, barren land, deciduous forest, evergreen forest, mixed forest, shrub scrub, herbaceous land, hay pasture, cultivated crops, woody wetlands and, emergent herbaceous wetlands by the percentage of land cover (NLCD, n.d.). Elevation and the land use parameters were resampled to the ~1 km grid cells. Land usage data were obtained for the years 2008, 2011, 2013, 2016, and 2019 and scaled in accordance with NASA PM2.5 Satellite coordinates used in this study.

Site Selection

The South Coast Air Basin including Coachella Valley was chosen as the study domain due to concerns about high levels of warehousing, commerce, distribution, and traffic-related pollutants, and the availability of air quality and spatial data. On the recommendation of partners at SCAQMD, the South Coast Air Basin and Salton Sea Air Basin were chosen to form the basis of the study domain. Communities of interest included in this region are San Bernardino, Riverside, and Los Angeles. These communities were chosen due to ongoing work in these areas by SCAQMD, and concerns for environmental justice impacts to local community members and high warehousing and commerce burden. A rectangular domain was selected around this region with a buffer of about ~5 km. All datasets previously mentioned were subsetted to this domain.

Similarly, the Chicago domain of interest was chosen on recommendation from the study partner at Muckrock Journalism. The domain was chosen to include select communities of interest including Cicero, Alsip, and Hegewisch as well as expanding to the greater metropolitan Chicago region. These communities were chosen due to concerns for historic redlining, oppression, and vulnerability to commerce-associated air pollution and warehousing activities. Similarly, a rectangular domain was selected around this region with a buffer of about ~5 km. All datasets previously mentioned were subsetted to this domain as well.

Data Analysis

Data Processing. All data processing was completed in R Studio, Excel, and ArcGIS Pro V2.9/3.0. First, MAIAC/MODIS PM2.5 and NO2 Satellite Data were used to create a study grid domain. A 1km grid around each satellite point was constructed using the Create Thiessen Polygons tool within ArcGIS Pro. CoStar warehousing was joined to this grid for both regions to merge datasets to a common ID. The CalEnviroScreen 3.0 2018 was joined to the grid via latitude and longitude within a certain grid cell as well.

Satellite Calibration Models. Satellite data was calibrated to ground data using two models for (PM2.5 and NO2). Satellite measurements and ground measurements were first joined to study grid domains and merged to create a training dataset. Satellite data was calibrated using the ranger function; a fast implementation of random forests or recursive partitioning (Breiman, 2001). For the calibration models, response variables were PM2.5 and NO2 ground measurements with predictor variables; latitude, longitude, and land use variables listed below. For California and Chicago, land usage data was included in the calibration model to improve the accuracy of satellite prediction data.

Models

PM2.5 Ground ~ PM2.5 Satellite + Latitude + Longitude + Open Water + Developed Open Space + Developed Low Intensity + Developed Medium Intensity + Developed High Intensity + Barren Land Deciduous Forest + Evergreen Forest + Mixed Forest + Shrub Scrub + Herbaceous + Hay Pasture + Cultivated Crops + Woody Wetlands + Emergent Herbaceous Wetlands

NO2 Ground ~ NO2 Satellite + Latitude + Longitude + Open Water + Developed Open Space + Developed Low Intensity + Developed Medium Intensity + Developed High Intensity + Barren Land Deciduous Forest + Evergreen Forest + Mixed Forest + Shrub Scrub + Herbaceous + Hay Pasture + Cultivated Crops + Woody Wetlands + Emergent Herbaceous Wetlands

Linear Regression Models. To assess the relationship between CoStar Warehousing square footage, demographic variables, and satellite PM2.5 and NO2 from 2010-2020 we decided to use a linear regression model. Our models compare warehouse size and satellite data to construct a regression model on a spatial scale for both Chicago and California. Ground and satellite data were compared at an annual average level within the Southern California and Chicago domains from 2010-2020 on a temporal scale. Data were modeled using a linear regression model accounting for satellite, warehouse size (square feet), and year. The secondary analysis includes demographic variables including poverty, unemployment, race & ethnicity, and annual average daily traffic (AADT) depending on location. A new variable was created to exclude warehouses below the large warehouse (100,000 sq ft.) designation by the Warehouse Indirect Source Rule (AQMD).

Southern California

Model 1: Calibrated PM 2.5 ~ Warehouse Sq. ft.

Model 2: Calibrated PM 2.5 ~ Warehouse Square Feet + CES 3.0 Score + Traffic + Pollution Burden Percentile + Education Percentile + Poverty Percentile

Model 3: Calibrated NO2 ~ Warehouse Sq. ft.

Model 4: Calibrated NO2 ~ Warehouse Square Feet + CES 3.0 score + Traffic + Pollution Burden Percentile + Education Percentile + Poverty Percentile

Chicago

Model 5: Calibrated PM 2.5 ~ Warehouse Sq. ft.

Model 6: Calibrated PM 2.5 ~ sqft_per_100000 + Minority Percentile + Low-Income Percentile + Traffic

Model 7: Calibrated NO2 ~ Warehouse Sq. ft.

Model 8: Calibrated NO2 ~ sqft_per_100000 + Minority Percentile + Low-Income Percentile + Traffic

Results & Discussion

Southern California

Table 1a: Annual summary statistics for ground and satellite NO2 measurements

NO2				
Year	**# Ground Monitors**	**Ground Annual Average**	**Satellite Annual Average (Raw)**	**Satellite Annual Average (Calibrated)**
2010	27	0.017802979	6.027651	0.01197947
2011	29	0.01647325	5.875259	0.0119393
2012	28	0.016223514	5.744508	0.0119105
2013	28	0.015515036	5.416903	0.01183541
2014	28	0.015315523	5.246437	0.01180484
2015	30	0.016391263	5.060736	0.0117643
2016	29	0.015510234	5.003862	0.01174856
2017	29	0.015457267	4.89506	0.01173268
2018	28	0.015068976	4.67379	0.01167674

2019	28	0.014079157	4.356439	0.01160774
2020	31	0.013640194	4.2903	0.01160289

The table shows the results of NO2 levels measured by ground monitors and satellites from 2010 to 2020. NO2 levels have decreased over time. Satellite annual averages have been calibrated to match the ground annual averages, and the calibrated values are consistently lower than the raw values.

Table 1b: Annual summary statistics for ground and satellite PM 2.5 measurements

PM 2.5				
Year	**# Ground Monitors**	**Ground Annual Average**	**Satellite Annual Average (Raw)**	**Satellite Annual Average (Calibrated)**
2010	14	15.32646	7.143234	11.63019
2011	15	16.33511	7.707533	11.70774
2012	16	14.25266	7.696693	11.67609
2013	16	13.11552	7.631631	11.65872
2014	15	14.86406	7.828045	11.73663
2015	15	14.47263	7.139325	11.59301
2016	15	12.75007	7.480146	11.63358
2017	16	13.62543	7.675696	11.70498
2018	15	12.82532	7.850575	11.7112
2019	15	10.31577	6.682206	11.50327
2020	18	13.43645	8.247166	11.81061

PM 2.5 levels have decreased over time, however, there are some fluctuations in the data from year to year. The satellite annual averages have been calibrated to match the ground annual averages, and the calibrated values are consistently higher than the raw values.

Table 1c: Random Forest Calibration Models

	# of Trees	n	MSE	R Squared (OOB)
Model 1 PM2.5	5	4.80E+01	0.9781722	0.5445344
Model 2 NO2	5	3.20E+01	9.971691	0.5311141

Model 1 (PM2.5) has a higher MSE and R-squared value than Model 2 (NO2), indicating that the PM2.5 model has better predictive performance. The R-squared values for both models are relatively low, which suggests that the models may not explain a large proportion of the variance in the data. There may be other factors that influence the levels of PM2.5 and NO2 that are not captured in the models. Additionally, the models are based on a relatively small number of trees (n=5), which may not be sufficient for accurate predictions. Overall, while the results suggest that the PM2.5 model is more accurate than the NO2 model, further research is needed to develop more robust models and explore the factors that influence air pollution levels.

Table 1d: Southern California Linear Regression Models

	Estimated Std.	Error	t value	Pr(>|t|)	95-CI
Model 1 PM2.5					
Intercept	1.45E+01	1.35E-02	1073.49	<2e-16 ***	14.43293 - 14.48573
Warehouse Sq. ft.	9.07E-13	4.74E-14	19.13	<2e-16 ***	8.143556E-13 - 1.00026E-12
Model 2 PM2.5					
Intercept	1.11E+01	4.91E-02	225.867	< 2e-16 ***	1.098194e+01 - 1.117421e+01
Warehouse Sq. ft.	4.54E-13	4.00E-14	11.343	< 2e-16 ***	3.756119e-13 - 5.325377e-13
CES 3.0 Score	1.79E-02	1.45E-03	12.386	< 2e-16 ***	1.508251e-02 - 2.075387e-02
Traffic	-8.69E-05	1.31E-05	-6.622	3.66e-11	-1.125762e-04 - -

				***	6.115019e-05
Pollution Burden Percentile	3.37E-02	7.51E-04	44.853	< 2e-16 ***	3.222856e-02-3.517411e-02
Education Percentile	1.03E-02	7.91E-04	13.013	< 2e-16 ***	8.743327e-03 - 1.184431e-02
Poverty Percentile	-8.99E-03	7.69E-04	-11.687	< 2e-16 ***	-1.049334e-02 - -7.479002e-03
Model 3 NO2					
Intercept	1.71E-02	2.49E-05	686.36	<2e-16 ***	1.702054e-02 - 1.711803e-02
Warehouse Sq. ft.	1.80E-15	8.76E-17	20.56	<2e-16 ***	1.628841e-15 - 1.972084e-15
Model 4 NO2					
Intercept	1.09E-02	9.33E-05	116.359	< 2e-16 ***	1.067011e-02 - 1.103575e-02
Warehouse Sq. ft.	1.10E-15	7.61E-17	14.441	< 2e-16 ***	9.500929e-16 - 1.248513e-15
CES 3.0 Score	1.43E-05	2.75E-06	5.199	2.03e-07 ***	8.910232e-06 - 1.969525e-05
Traffic	2.46E-07	2.50E-08	9.873	< 2e-16 ***	1.973940e-07 - 2.951892e-07
Pollution Burden Percentile	5.84E-05	1.43E-06	40.888	< 2e-16 ***	5.562245e-05 - 6.122391e-05
Education Percentile	1.86E-05	1.50E-06	12.341	< 2e-16 ***	1.561550e-05 - 2.151253e-05
Poverty Percentile	-7.83E-06	1.46E-06	5.355	8.65e-08 ***	-1.069669e-05 - -4.964424e-06

The coefficients of determination indicate that **Model 1** explains a small proportion of the variance in the dependent variable, with an R-squared of 0.01949 and an adjusted R-squared of 0.01944. This suggests that the independent variable included in Model 1 is not highly predictive of PM2.5 levels. The p-value associated with the F-statistic is very small (<2.2e-16), indicating that the overall model is statistically significant. Additionally, the p-value associated with the coefficient for Warehouse Sq. ft. is also very small (<2e-16), indicating that this variable is a statistically significant predictor of PM2.5 levels. Overall, the results of Model 1, suggest that while Warehouse Sq. ft. is a statistically significant predictor of PM2.5 levels, it explains only a small proportion of the variance. Additional variables may be needed to better predict PM2.5 levels. In **Model 2**, the coefficients of determination indicate that the model explains a significant proportion of the variance in the dependent variable, with an R-squared of 0.3214 and an adjusted R-squared of 0.3212. This suggests that the independent variables included in the model are predictive of PM2.5 levels. The p-value associated with the F-statistic is very small (<2.2e-16), indicating that the overall model is statistically significant. Additionally, the p-values associated with the coefficients for all the independent variables are also very small (<2e-16), indicating that all these variables are statistically significant predictors of PM2.5 levels. Overall, the results suggest that the model is a good fit for the data and that the six independent variables included in the model are statistically significant predictors of PM2.5 levels.

In **Model 3**, the coefficients of determination indicate that the model explains a small proportion of the variance in the dependent variable, with an R-squared of 0.02245 and an adjusted R-squared of 0.02239. This suggests that the independent variable included in the model is not highly predictive of NO2 levels. The p-value associated with the F-statistic is very small (<2.2e-16), indicating that the overall model is statistically significant. Additionally, the p-value associated with the coefficient for Warehouse Sq. ft. is also very small (<2e-16), indicating that this variable is a statistically significant predictor of NO2 levels. Overall, the results suggest that while Warehouse Sq. ft. is a statistically significant predictor of NO2 levels, it explains only a small proportion of the variance. Additional variables may be needed to better predict NO2 levels.

In **Model 4**, the coefficients of determination indicate that the model explains a significant proportion of the variance in the dependent variable, with an R-squared of 0.282 and an adjusted R-squared of 0.2818. This suggests that the independent variables included in the model are predictive of NO2 levels. The p-value associated with the F-statistic is very small (<2.2e-16), indicating that the overall model is statistically significant. Additionally, the p-values associated with the coefficients for all the independent variables are also very small (<2e-16), indicating that all these variables are statistically significant predictors of NO2 levels. Overall, the results suggest that the model is a good fit for the data and that the six independent variables included in the model are statistically significant predictors of NO2 levels. These models indicate that vulnerable individuals living below the poverty line, with less access to education and a significant pollution burden, are also exposed to more traffic and in proximity to larger warehousing square footage and higher levels of PM2.5 and NO2.

Metropolitan Chicago

Table 2a: Annual summary statistics for ground and satellite NO2 measurements in Chicago

NO2				
Year	**# Monitors**	**Ground Annual Average**	**Satellite Annual Average (Raw)**	**Satellite Annual Average (Calibrated)**
2010	4	34.4357	21.79642	33.69415
2011	4	33.79766	20.47577	33.62269
2012	3	33.97256	19.52963	33.51363
2013	3	33.59881	18.03072	33.2391
2014	3	33.19208	17.01486	32.92814
2015	3	29.20658	16.09852	32.55874

2016	3	29.65543	15.70082	32.35324
2017	3	27.6114	15.56337	32.22573
2018	2	30.40936	15.07419	31.90861
2019	3	26.64888	15.58308	32.11095
2020	3	25.75192	15.06086	31.93039

Satellite annual averages have been calibrated to match the ground annual averages, and the calibrated values are consistently lower than the raw values. The number of monitors used has varied over the years, with the highest number in 2011 and the lowest number in 2018.

Table 2b: Annual summary statistics for ground and satellite PM 2.5 measurements in Chicago

PM 2.5				
Year	**# Monitors**	**Ground Annual Average**	**Satellite Annual Average (Raw)**	**Satellite Annual Average (Calibrated)**
2010	9	12.422958	12.132653	11.477099
2011	17	11.863511	11.811225	11.445147
2012	5	10.678834	11.380466	11.231012
2013	7	10.459694	10.775364	10.742962
2014	7	10.934788	11.00277	10.904089
2015	7	10.422659	10.106268	10.301944
2016	7	8.754784	8.646064	9.634875
2017	7	8.822541	8.6207	9.621849
2018	7	9.467725	9.379155	9.784698
2019	7	9.74294	9.125656	9.700776
2020	7	8.841283	8.850437	9.651016

PM2.5 levels have generally decreased over time, with some fluctuations from year to year. The number of monitors used has also varied over the years, with the highest number in 2011 and the

lowest number in 2012. The satellite annual averages have been calibrated to match the ground annual averages, and the calibrated values are consistently lower than the raw values.

Table 2c: Random Forest Calibration Models

	# of Trees	n	MSE	R Squared (OOB)
Model 1 PM 2.5	5.00E+02	1.75E+02	4.51785	0.692288
Model 2 NO2	5.00E+02	2.95E+02	2.27E-06	0.9253939

Model 1 (PM2.5) has a lower MSE and R-squared value than Model 2 (NO2), indicating that the PM2.5 model has better predictive performance. The R-squared value for Model 1 suggests that the model explains a relatively high proportion of the variance in the data, while the R-squared value for Model 2 is extremely low, indicating that the model may not be a good fit for the data.

Table 2d: Chicago Linear Regression Models

	Estimated Std.	Error	t value	Pr(>|t|)	95-CI
Model 5 PM 2.5					
Intercept	1.04E+01	1.60E-02	650.518	<2e-16 ***	1.035595e+01 - 1.041856e+01
Warehouse Sq. ft.	2.51E-13	4.73E-13	0.531	0.595	-6.765706e-13 - 1.179369e-12
Model 6 PM 2.5					
Intercept	1.03E+01	4.15E-02	248.763	<2e-16 ***	1.023535e+01 - 1.039798e+01
Warehouse Sq. ft.	1.77E-13	4.74E-13	0.373	0.709	-7.526444e-13 - 1.106487e-12
Minority Percentile	1.48E-01	7.44E-02	1.988	0.0468 *	2.063544e-03 - 2.937159e-01

Low Income Percentile	-5.63E-02	1.02E-01	-0.553	0.58	-2.556661e-01 - 1.431077e-01
Traffic	-4.09E-06	4.16E-06	-0.983	0.3256	-1.224178e-05 - 4.065092e-06
Model 7 NO2					
Intercept	3.30E+01	2.82E-02	1167.694	< 2e-16 ***	3.292182e+01 - 3.303256e+01
Warehouse Sq. ft.	-4.79E-12	8.37E-13	-5.725	1.13e-08 ***	-6.433217e-12 - - 3.150700e-12
Model 8 NO2					
Intercept	3.27E+01	7.28E-02	448.941	< 2e-16 ***	3.251665e+01 3.280193e+01
Warehouse Sq. ft.	-4.82E-12	8.32E-13	-5.793	7.61e-09 ***	-6.447920e-12 - - 3.186740e-12
Minority Percentile	8.96E-01	1.31E-01	6.87	7.71e-12 ***	6.404783e-01 - 1.152078e+00
Low-Income Percentile	-7.93E-01	1.78E-01	-4.443	9.17e-06 ***	-1.142343e+00 - - 4.428373e-01
Traffic	2.65E-05	7.29E-06	3.632	0.000286 ***	1.218913e-05 - 4.079369e-05

In **Model 5**, the coefficients of the determination indicate that the model explains a very small and insignificant proportion of the variance in the dependent variable, with an R-squared of 8.994e-05 and an adjusted R-squared of -0.0002288. This suggests that the independent variable included in the model is not predictive of PM2.5 levels. The p-value associated with the F-statistic is not statistically significant (p-value: 0.5953), indicating that the overall model is not statistically significant. Additionally, the p-value associated with the coefficient for Warehouse Sq. ft. is also not statistically significant (p-value: 0.595), indicating that this variable is not a significant predictor of PM2.5 levels. Overall, the results suggest that the model is not a good fit for the data and that the independent variable, Warehouse Sq. ft. is not a statistically significant predictor of

PM2.5 levels. In **Model 6**, the coefficients of determination indicate that the model explains a very small and insignificant proportion of the variance in the dependent variable, with an R-squared of 0.002321 and an adjusted R-squared of 0.001047. This suggests that the independent variables included in the model are not strong predictors of PM2.5 levels. The p-value associated with the F-statistic is not statistically significant (p-value: 0.1216), indicating that the overall model is not statistically significant. Additionally, the p-values associated with the coefficients for Warehouse Sq. ft., Low Income Percentile, and Traffic are also not statistically significant (p-values: 0.709, 0.58, and 0.3256, respectively), indicating that these variables are not significant predictors of PM2.5 levels. However, the p-value associated with the coefficient for Minority Percentile is statistically significant (p-value: 0.0468), indicating that this variable is a significant predictor of PM2.5 levels. Overall, the results suggest that the model is not a good fit for the data and that the independent variables included in the model are not strong predictors of PM2.5 levels, except for Minority Percentile.

In **Model 7**, the coefficient of determination indicates that the model explains a small but statistically significant proportion of the variance in the dependent variable, with an R-squared of 0.01034 and an adjusted R-squared of 0.01002. This suggests that Warehouse Sq. ft. is a weak but statistically significant predictor of NO2 levels. The p-value associated with the F-statistic is statistically significant (p-value: 1.134e-08), indicating that the overall model is statistically significant. Additionally, the p-value associated with the coefficient for Warehouse Sq. ft. is also statistically significant (p-value: 1.13e-08), indicating that this variable is a significant predictor of NO2 levels. Overall, the results suggest that Warehouse Sq. ft. is a weak but statistically significant predictor of NO2 levels, with a negative coefficient indicating that as Warehouse Sq. ft. increases, NO2 levels decrease. However, the small R-squared value indicates that there may be other factors that influence NO2 levels that are not accounted for in the model. In **Model 8**, results indicate that the intercept term is statistically significant, as well as the predictor variables for the minority percentile, low-income percentile, and traffic. The coefficient for warehouse square footage is negative but not statistically significant. The adjusted R-squared value of the model is relatively low, indicating that the predictor variables explain only a small proportion of the variance in the data. The model may have limitations, such as potential confounding variables that are not included in the model or measurement errors in the predictor variables. Additionally, the deletion of 11 observations due to missingness may have impacted the accuracy of the model. Overall, further research is needed to develop more robust models and to better understand the factors that influence NO2 levels.

The results presented in this study show that both NO2 and PM2.5 levels in Southern California and metropolitan Chicago have decreased over time which is inconsistent with the hypothesis that increased warehousing activity has impacted and contributed to increased levels over time. This may be impacted by local legislation and efforts to curb pollutants and improve air quality as well.

The random forest calibration models suggest that the PM2.5 model has better predictive performance than the NO2 model, but further research is needed to develop more robust models and explore the factors that influence air pollution levels. The use of Linear Regression modeling for analysis contributes to more clear communication of results for study partners and community members. In Southern California, Model 2 for PM2.5 and Model 4 for NO2 have coefficients of determination indicating that the models explain a significant proportion of the variance in the dependent variable, with all independent variables included in the models being statistically significant predictors of PM2.5 and NO2 levels. The results suggest that additional variables may be needed to better predict PM2.5 levels in Model 1 and NO2 levels in Model 3. For metropolitan Chicago, both NO2 and PM2.5 levels have generally decreased over time, with some fluctuations from year to year. However, the number of monitors used has varied over the years and is limited, which could affect the accuracy of the results.

Looking at warehousing distribution in Southern California (Figure 1a), there is a concentration of warehouses within San Bernardino and Riverside counties as well as along major traffic byways. Ground monitoring in California is some of the most comprehensive in the country with ~30-35 PM2.5 and NO2 sensors from the AQMIS database. Additionally, hundreds of low-cost purple air sensors have been deployed throughout this region that were not included in this analysis. Purple air was not included due to difficulty accessing appropriate time frames of data. The large majority of Purple Air measurements have been obtained since 2016, while this study timeframe spanned 2010-2020. Satellite data was calibrated to the predetermined domain encompassing parts of the South Coast Air Basin and Salton Sea Air Basin (Figure 1c, Figure 1d, Figure 1e). Calibration of the Southern California domain was robust due to a significant number of ground sensors and adequate coverage. Looking at the variation of PM.25 levels from 2010-2020, there is a general decrease in measured PM2.5 since 2010 which may be attributed to increased regulation and monitoring of air quality in the region thanks to the AQMD (Figure 1f). Similarly, NO2 levels have varied with more significant highs and a general downward trend (Figure 1g).

Similarly in Chicago, warehouses are concentrated along major roads and in western and southern neighborhoods, which are composed of historically marginalized communities (Figure 2a). Looking at the distribution of EPA sensors, there are limited monitoring locations, suggesting a need for increased monitoring in southern and western neighborhoods of Chicago as well as along traffic corridors (Figure 2b). This analysis was limited by the lack of ground monitors to calibrate satellite data and thus is difficult to use to predict changes in air pollution or specific neighborhood-level impacts. The Calibration of PM2.5 and NO2 was not robust due to limited ground data (Figure 2d, Figure 2e). Looking at annual variation, there is a significant downward trend in annual measured PM 2.5 and NO2 from ground sensors which may be attributed to the increasing monitoring of air pollutants in the region (Figure 2f, Figure 2g). This is not explained by increased warehousing and commerce activity, however. Overall, these findings suggest that efforts to reduce air pollution in both regions have been successful and that warehousing activity in both regions may be associated with it, but further research is needed to develop more accurate models and to identify additional factors that contribute to air pollution.

Conclusion

In Southern California, the boom in warehousing and commerce-related activities has contributed to increased diesel trucking and distribution activities. Communities living near these warehouses and roadways, are historically marginalized and have reduced access to clean air as a result. Through this analysis, it is apparent that PM2.5 and NO2 concentrations are significantly associated with increasing warehousing sizes, traffic counts, pollution burden, and individuals most at risk due to poverty and reduced education. Similarly in Chicago, NO2 levels due to diesel and transportation emissions are significantly associated with increasing warehouse sizes, traffic, and individuals within minority and low-income demographics. In Chicago, PM2.5 is not significantly associated with warehousing activity but is associated with communities composed of largely minority groups. Together, this analysis builds the case for an important environmental justice issue and further research into the corporations responsible for commerce activities, and specific neighborhoods that are most at risk. Further analysis is needed, as well as more robust neighborhood-level monitoring in both regions. These results were completed in partnership with the SCAQMD and MuckRock Journalism and will be used to inform community conversation and future research projects.

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Figures

Southern California

Figure 1a: Warehouses in the Inland Empire (indoor sq. footage ≥ 100,000 sq. ft)

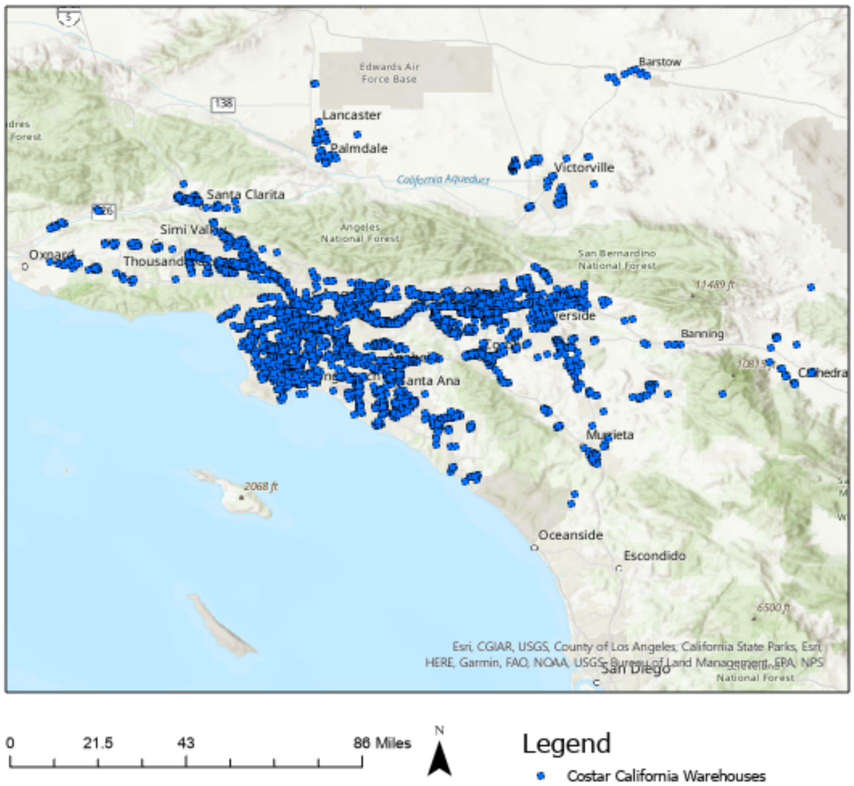


Figure 1b: AQMIS PM 2.5 & NO2 Ground Sensor Locations

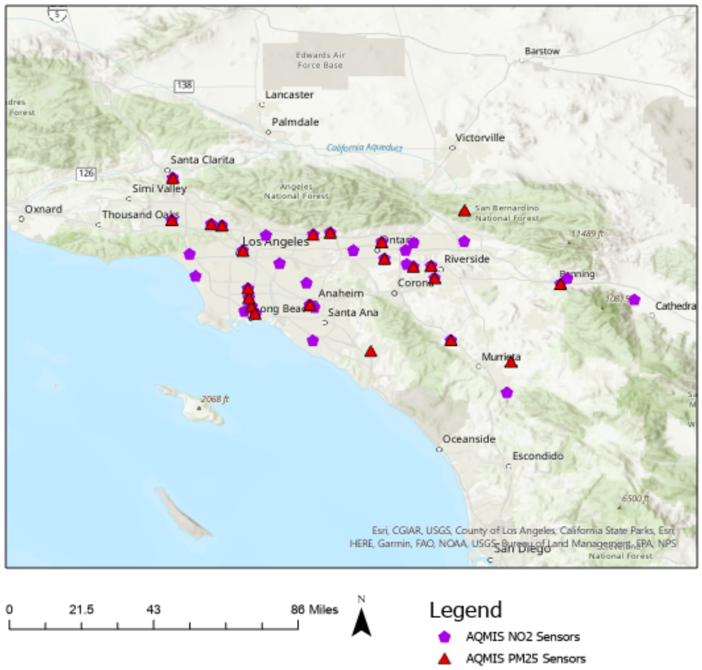


Figure 1c: California Domain with NASA MODIS PM2.5-based Grid

Figure 1d: PM 2.5 Calibrated Satellite Data (μg/m3)

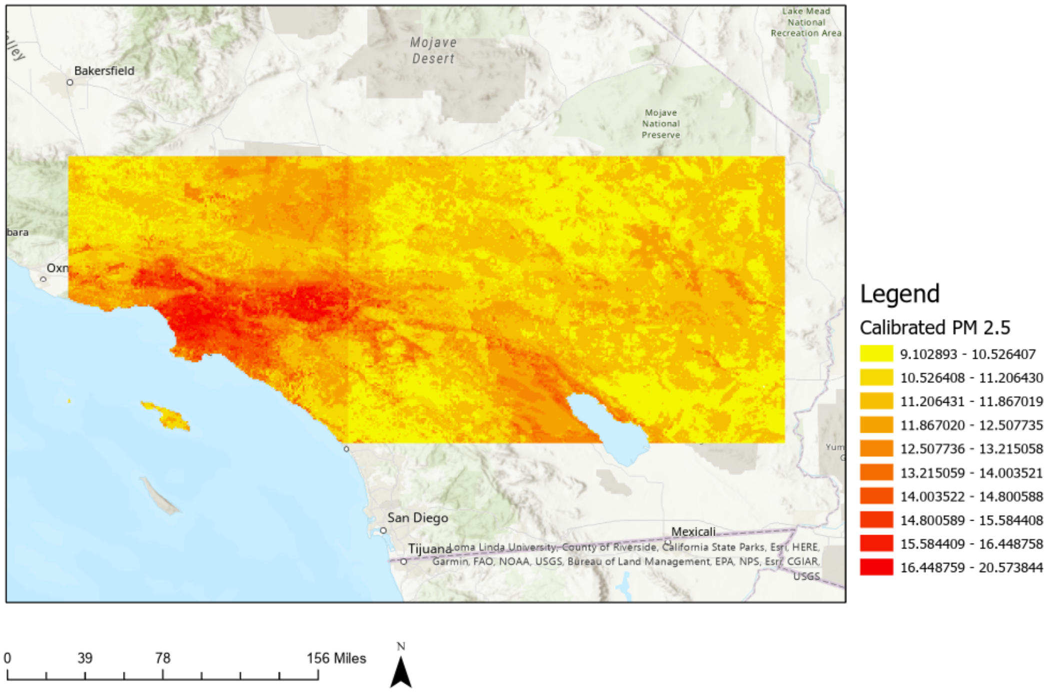


Figure 1e: NO2 Calibrated Satellite Data (ppm)

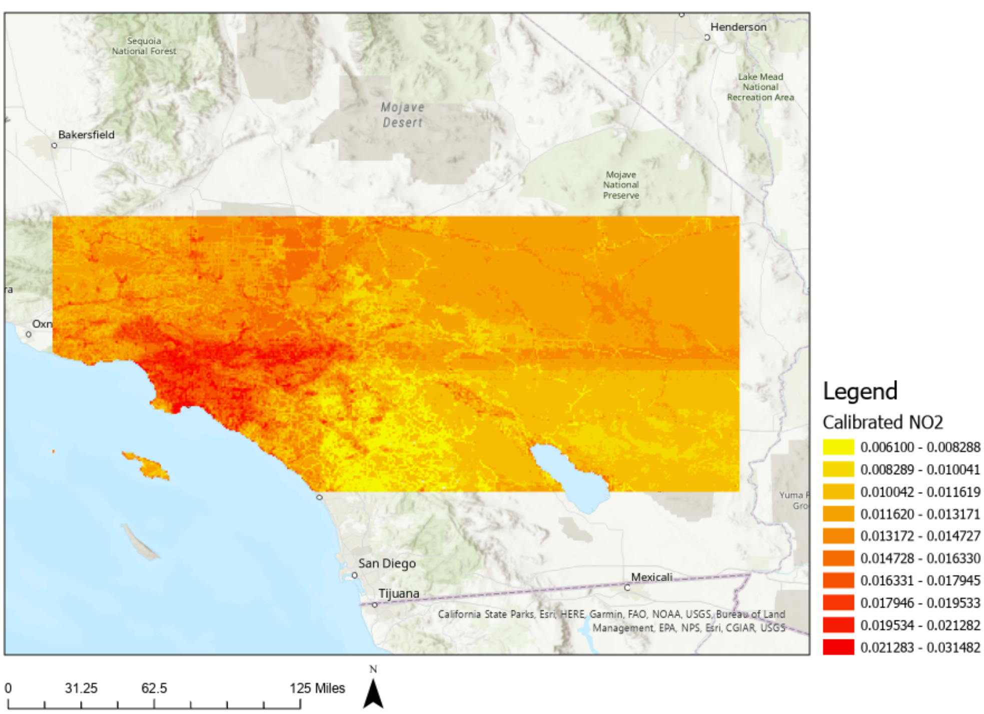


Figure 1f: Annual Average AQMIS PM 2.5 Levels by Year

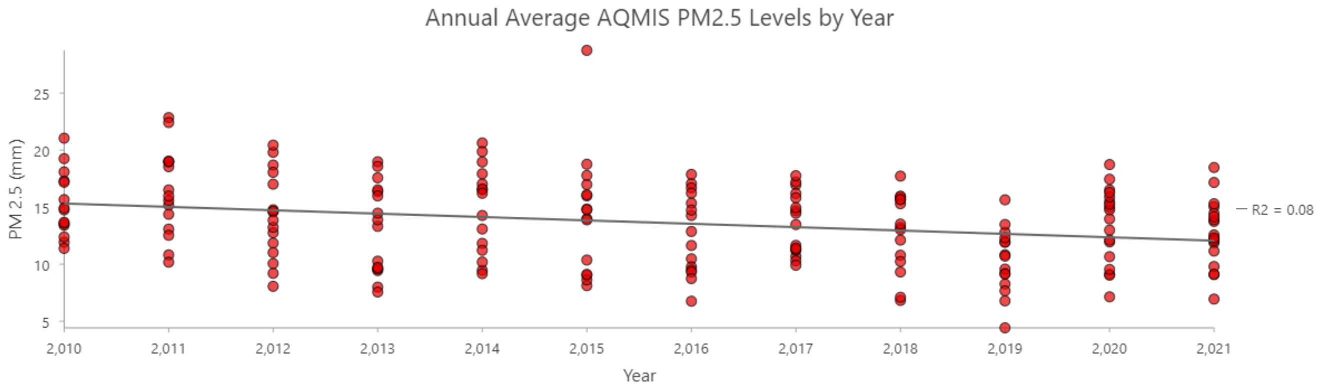
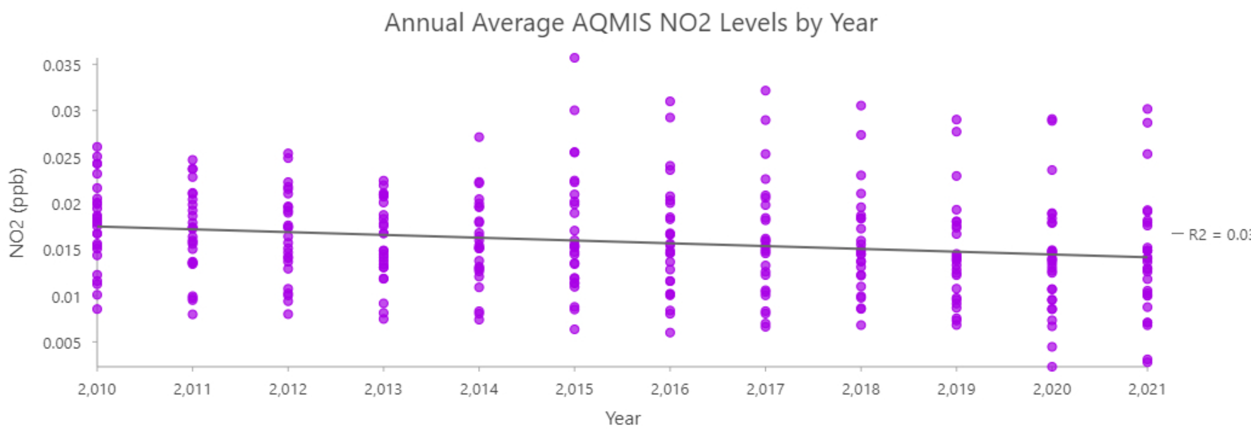


Figure 1g: Annual Average AQMIS NO2 Levels by Year (AQMIS Ground Monitors)



Metropolitan Chicago

Figure 2a: Warehouses in the Chicago Metropolitan Area (indoor sq. footage ≥ 100,000 sq. ft)

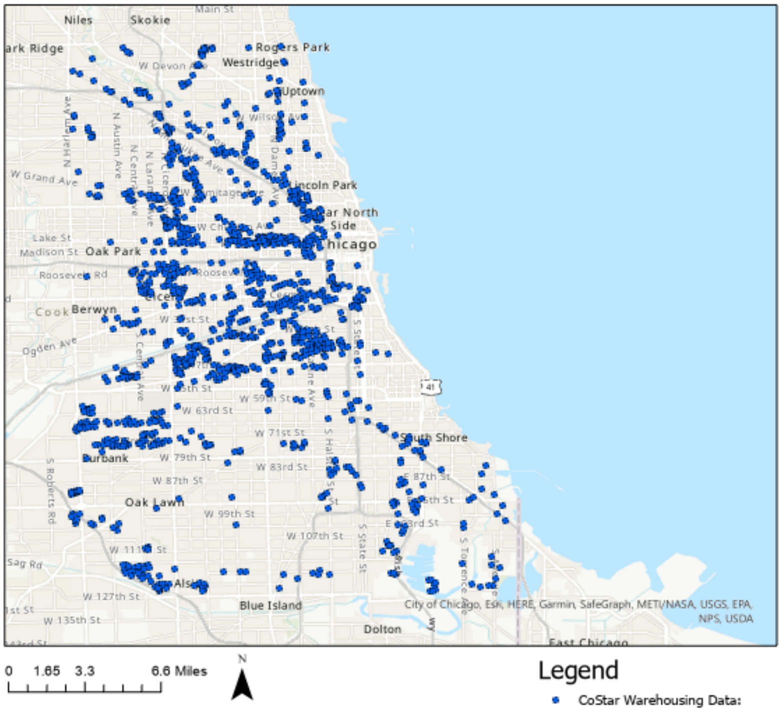


Figure 2b: EPA PM2.5 & NO2 Ground Sensor Locations

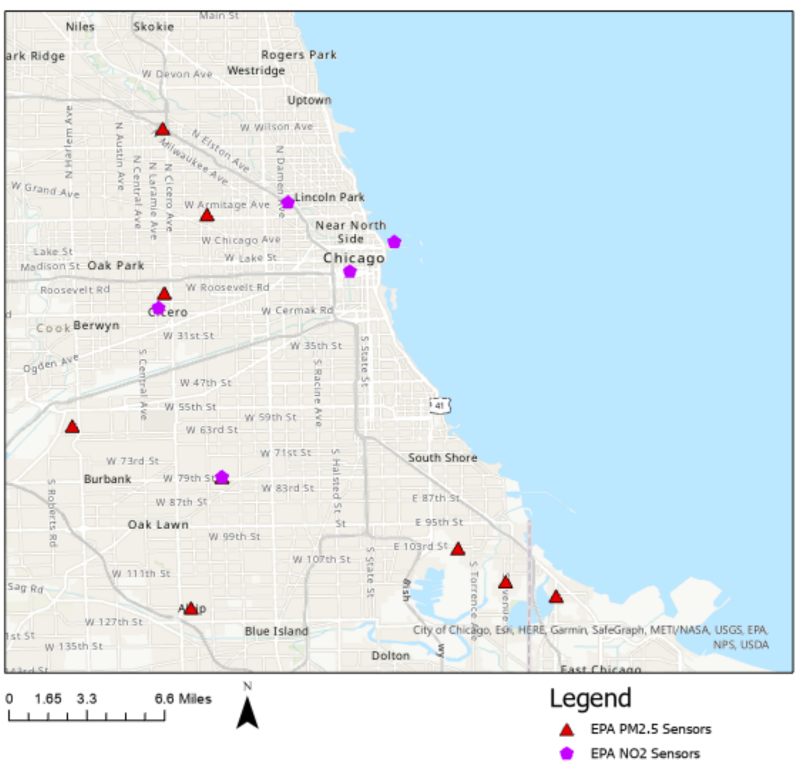


Figure 2c: Chicago Domain with NASA MODIS PM2.5-based Grid

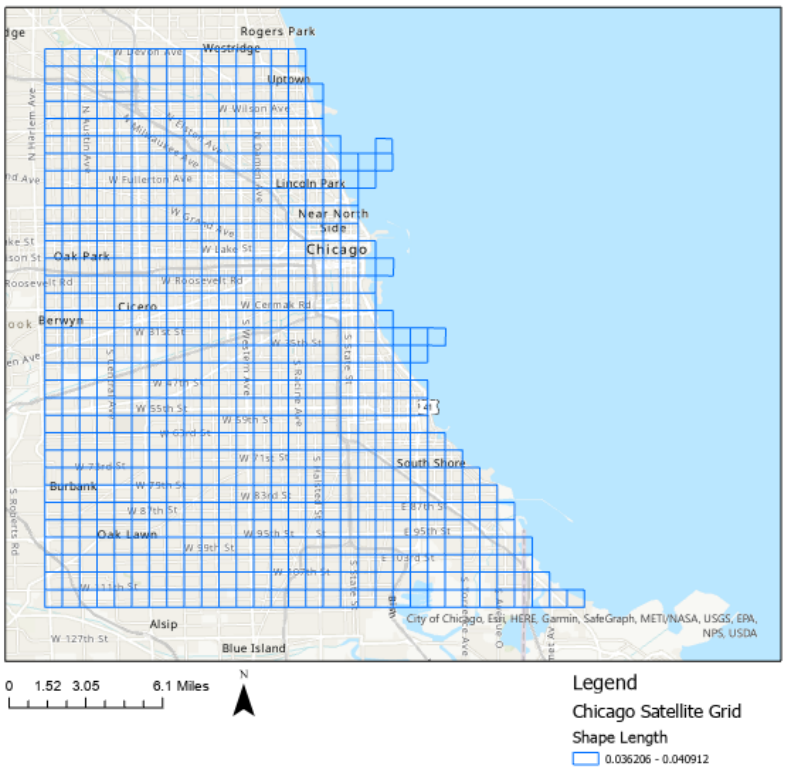

Rogers Park
Westridge
Uptown
Lincoln Park
Near North Side
Chicago
Oak Park
Cicero
Berwyn
South Shore
Burbank
Oak Lawn
Alsip
Blue Island
City of Chicago, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, EPA, NPS, USDA
0 1.52 3.05 6.1 Miles
N
Legend
Chicago Satellite Grid
Shape Length
0.036206 - 0.040912

Figure 2d: PM 2.5 Calibrated Satellite Data (µg/m3)

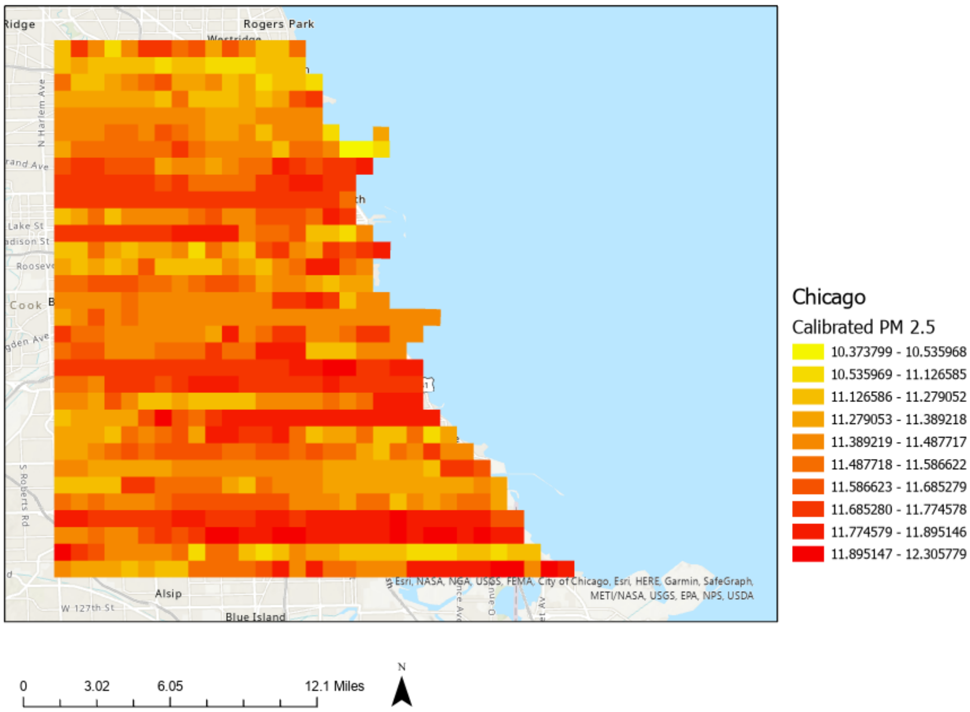


Figure 2e: NO2 Calibrated Satellite Data (ppm)

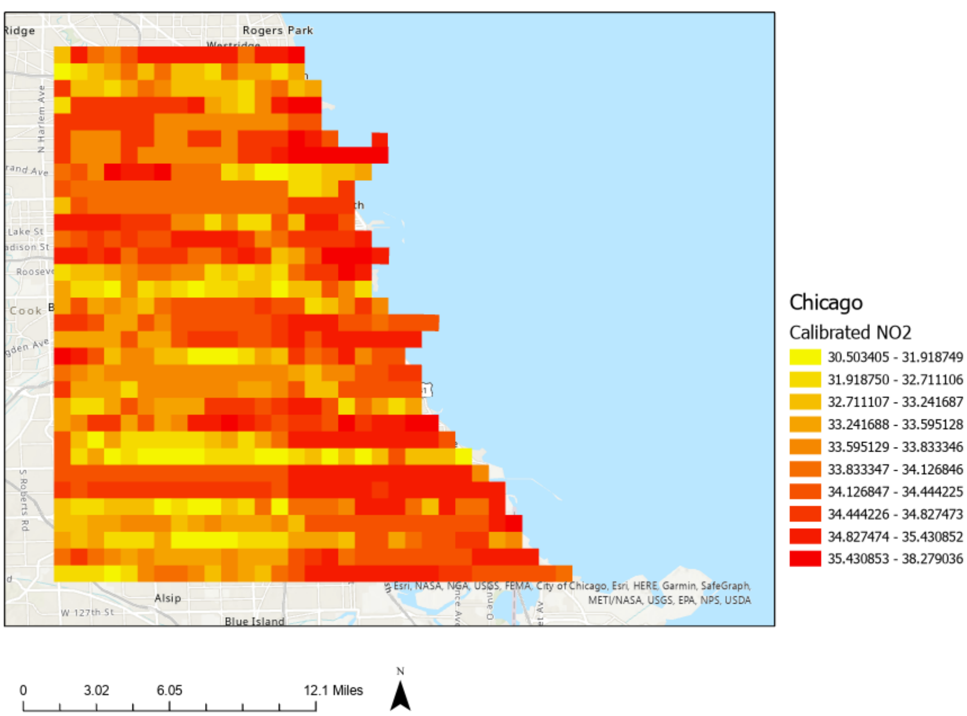


Figure 2f: Daily Average EPA PM 2.5 Levels by Year (EPA Ground Monitors)

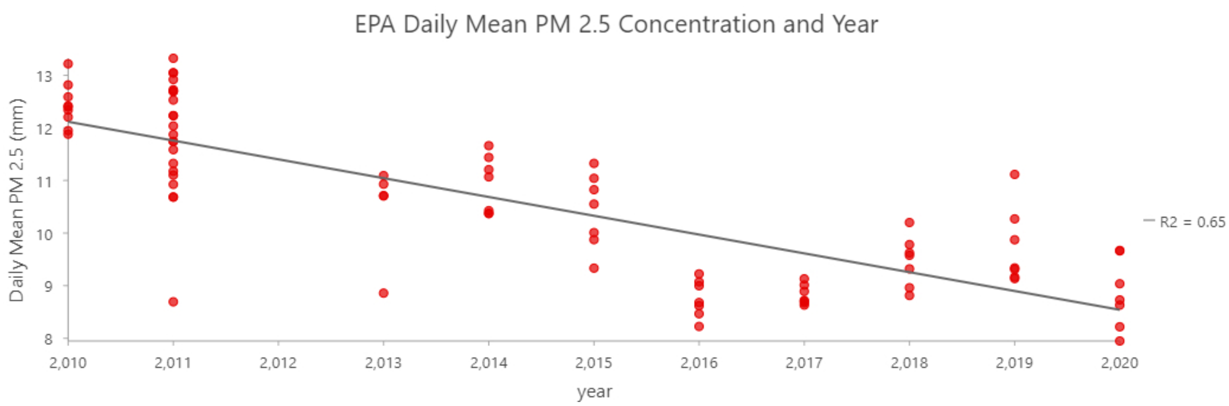


Figure 2g: Daily Average EPA NO2 Levels by Year (EPA Ground Monitors)