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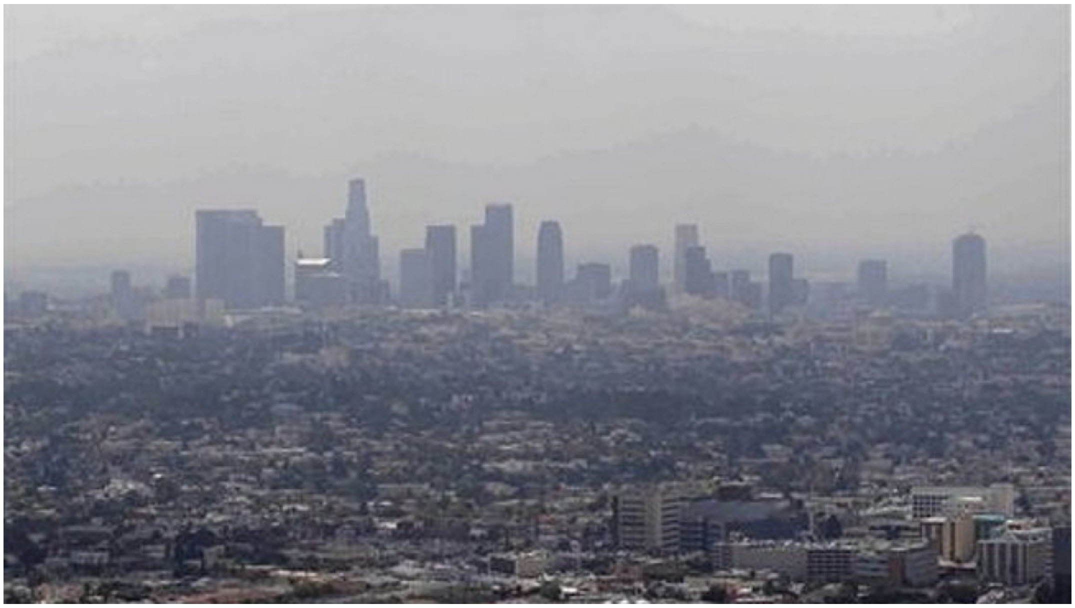

The Environmental Justice Implications of Air Pollution Changes Following COVID-19 Stay at Home Policies in San Diego County

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Abstract

COVID-19 policies impacted fine particulate matter (PM2.5) levels in San Diego County. This study looked at the benefits of COVID-19-related policies and changes in PM2.5 levels across ZIP codes in San Diego County. Weekly PM2.5 anomalies were calculated for each ZIP code by subtracting the average PM2.5 concentrations of 2020 by average of the historical period (2000 - 2019). Five periods were selected for individual analyses based on the different COVID-19 policies and measures implemented. These policies involved the first stay-at-home order (analysis #1), summer restrictions (analysis #2), the second stay-at-home order (analysis #3), the average of analyses 1-3, (analysis #4), and the wildfire season (analysis #5). PM2.5 anomalies and seven different socioeconomic status (SES) variables were mapped to show any spatial variability. Linear regression models were used to quantify the relationship between SES variables and PM2.5 anomalies for each analysis. The first stay-at-home order (analysis #1) had the lowest PM2.5 anomalies across the County. Analysis #5, on the other hand, had the highest positive anomalies. COVID-19 mobility restrictions and the associated short-lived decline in air pollution influenced the ZIP codes differently. South San Diego County is a greatly disadvantaged area with high unemployment rate, low income, high poverty rate, and less education compared to others within the County. A significant inverse relationship was observed between the percentage of African American within a given ZIP code and PM2.5 anomalies. Future policies need to tackle health disparities, which involves stringent policies, a better public transit system, community advocacy, and cleaner technology.

Project Motivation

The Coronavirus (COVID-19) pandemic continues to impact human populations and natural environments worldwide. A few studies have assessed the impact of mobility restrictions and the decline of economic activity on air pollution levels (Cicala et al., 2020; Venter et al., 2020; Liu et al., 2020) and environmental justice implications. To this day, air pollution remains one of the major environmental threats to public health (Gkatzelis et al., 2021). Previous studies found that the COVID-19 related policies and restrictions resulted in better air quality for a short period of time in some regions such as California (Venter et al., 2020; Liu et al., 2020), though different communities may experience disproportionate impacts of both COVID-19 and air pollution (Mitchell et al., 2015).

1. Introduction and Background

1.1. Air Pollution and Fine Particulate Matter ($PM_{2.5}$)

Air pollution, which is often of anthropogenic origin, has harmful effects on human health and our natural environment. According to the World Health Organization (WHO), air pollution is the main environmental health risk globally, killing around seven million people per year each year (Gkatzelis et al., 2021). For outdoor air pollution (as opposed to indoor pollution), the associated annual morbidity toll is about 4.2 million people (Gkatzelis et al., 2021). Outdoor air pollution typically includes fine particles, noxious gasses (e.g., nitrogen oxides and carbon monoxide), and ground-level ozone in the atmosphere.

Fine particulate matter ($PM_{2.5}$) comprises tiny airborne particles that are a mixture of solid particles and liquid droplets with diameters that are less than 2.5 micrometers (**Figure 1**; EPA, 2020). Examples include dust, dirt, soot, and smoke, which can be emitted from different sources.

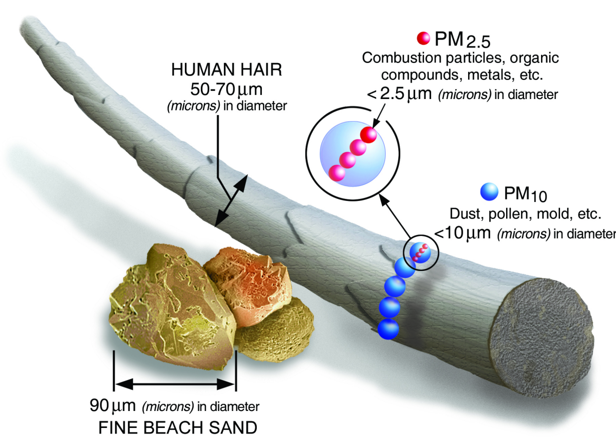

Figure 1: The size of PM particles (source: EPA)

$PM_{2.5}$ is a primary and secondary pollutant; this factor influences the $PM_{2.5}$ source. As a primary pollutant, $PM_{2.5}$ can be emitted from construction sites, unpaved roads, fields, smokestacks or fires (EPA, 2020). As a secondary pollutant, $PM_{2.5}$ can form in the atmosphere from reactions of other chemicals such as sulfur dioxide and nitrogen oxides; sulfur dioxide and nitrogen oxides can be emitted from power plants, automobiles, and industries (EPA, 2020). Therefore, $PM_{2.5}$ comes from many sources, but in this study, we will only focus on the traffic and transportation source. One of the main sources of $PM_{2.5}$ is traffic related air pollution (TRAP), a mixture of vehicle exhausts, secondary pollutants, evaporative emissions from vehicles, and non-combustion emissions (Matz et al., 2019). $PM_{2.5}$ can form TRAP emissions mainly from brake wear, tire wear, resuspended dust, and combustion (Askariyeh et al., 2020). Highway vehicles emit 0.1 million tons of $PM_{2.5}$ in the United States every year, whereas off-highway vehicles emit 0.173 million tons of $PM_{2.5}$ in the United States (Cicala et al., 2020). The usage of vehicles produces both the primary and secondary forms of $PM_{2.5}$ (Reichmuth, 2019).

$PM_{2.5}$ is a major concern since it can penetrate deep into the lungs and enter the bloodstream (EPA, 2020), potentially causing respiratory and cardiovascular illnesses and other impacts on human health. PM has been associated with premature death in people with heart or lung disease, aggravated asthma, decreased lung function, coughing, difficulty breathing, and nonfatal heart attacks (EPA, 2020). In addition, $PM_{2.5}$ has been observed to contribute to a total of 0.5 over three expected deaths per billion miles traveled in a study that looked at the United States (Cicala et al., 2020). Moreover, children and older adults are more vulnerable to $PM_{2.5}$ exposure and its effects on health (EPA, 2020).

1.2. Air Pollution Regulation

To tackle the effects of $PM_{2.5}$ pollution on public health, governments have implemented national and regional air pollution regulations. Air quality standards established the maximum amount that criteria pollutants, such as $PM_{2.5}$ and ozone, can be emitted in the atmosphere. At the US Federal level, the Clean Air Act (CAA) was enacted to control air pollution on a national level. Under the CAA, the EPA created the National Ambient Air Quality Standards (NAAQS), which set air quality standards for air pollutants like $PM_{2.5}$. Annual standards for $PM_{2.5}$ are 12 $\mu g/m^3$ for primary sources and 15 $\mu g/m^3$ for $PM_{2.5}$ coming from secondary sources. The 24-hour standard for both types of $PM_{2.5}$ pollution is 35 $\mu g/m^3$ (EPA, 2020).

At the state level, California Air Resources Board (CARB) oversees all air pollution control efforts, particularly those related to transportation and traffic sources. At the county level, the San Diego County Air Pollution Control District (APCD) monitors and regulates local air pollution (Network of Care, 2020). Overall, such agencies focus on compliance and air quality standards through air quality monitoring stations that take measurements of airborne pollutants on a daily basis (Fuller and Font, 2019). These policies mainly focus on attaining limits rather than targets for improvement; for instance, they do not focus on the rate of change and trends.

1.3. Disproportionate Exposure to Air Pollution

Environmental justice is a principle that everyone, regardless of their socio-economic status, ethnicity, and race, should fairly share the effects of environmental hazards and the benefits of environmental amenities. Therefore, disadvantaged communities should not be exposed to disproportionate environmental impacts such as poor air quality (Mitchell et al., 2015). However, African Americans and low-income populations are disproportionately exposed to pollution, toxic chemicals, and unwanted land uses across the United States (Wheeler, 2013, pp 74).

Environmental Justice started out as a social movement. One of the foundational events took place in 1982 in response to a toxic waste landfill affecting Warren County, North Carolina, which consists of an African American community; this led to many protests (Mitchell et al., 2015). In 1983, encouraged by the Warren County protests, the General Accounting Office (GAO) did a study on environmental racism to see a correlation between toxic waste landfill locations and the race and socioeconomic status of communities living near them in eight Southeastern states. They found that three out of the four main toxic waste landfill sites had mainly an African American community surrounding them; therefore, this study proved that environmental racism exists (Alabama Center, 2019; EPA, 2021).

In 1991, the First National People of Color Summit was held; the term, environmental justice, was expanded to include worker safety, housing, transportation, and public health (Alabama Center, 2019; EPA, 2021). In 1992, the EPA established the Office of Environmental Justice (OEJ), which focuses on incorporating environmental justice into all EPA programs, activities, and policies (EPA, 2021). In 1993, a federal advisory committee, National Environmental Justice Advisory Council (NEJAC), provided recommendations to stakeholders regarding environmental justice and held public meetings on these issues (Alabama Center, 2019; EPA, 2020). In 1994, President William J. Clinton issued Executive Order 12898 (EPA, 2021). For the Executive Order 12898, federal agencies address disproportionately health and environmental effects on minority and low-income populations and develop strategies to implement environmental justice (EPA, 2021). In 2012, EPA created the EJSCREEN, which is an environmental justice screening and mapping tool. In 2016, EPA announced the EJ 2020 Action Agenda, which focused on advancing environmental justice from 2016 to 2020 (EPA, 2021). These are the movements and regulations that acknowledge that environmental injustice exists; however, these conditions were created due to racist and discriminatory policies.

Oftentimes, marginalized communities end up living in highly polluted areas due to historical and current racist and discriminatory policies, such as redlining (Nardone et. al, 2020). Redlining was initiated in 1934 by the Federal Housing Administration (Nardone et. al, 2020) and it involved marking red lines on maps to specify certain neighborhoods where mortgages were denied to marginalized, racialized groups to steer them away from white neighborhoods (Bailey et al., 2017). For example, the Home Owners' Loan Corporation (HOLC) instilled the discriminatory practice of categorizing neighborhoods into four groups based on their qualifications for federal mortgage insurance guarantees (Nardone et. al, 2020). In California, San Diego was among the eight cities where redlining was implemented, in addition to cities like Los Angeles and San Francisco, with each census tract categorized into four risk levels (A, B, C, D; **Figure 2**; Nardone et. al, 2020). Level D represented the worst risk level for mortgage indicating historical redlining while level A was the lowest (**Figure 2**). The high risk level (level D) has been linked to asthma-related exposures, such as air pollution, psychosocial stress, and insufficient access to health care with exposure of 39.7% of diesel PM and 11.4% of $PM_{2.5}$. The study considered 1431 census tracts in California. The results regarding the 1431 census tracts were grade A: 4.5% (64 out of 1431 census tracts), grade B: 16.8% (241 census tracts), grade C: 50.2% (719 census tracts), and grade D: 28.4% (407 census tracts; Nardone et. al, 2020). At level D, there was a larger percentage of non-Hispanic black and Hispanic populations while at level

A, there was a larger percentage of non-Hispanic white populations. In addition, the poverty rate was 3.3 times higher in level D rated tracts than in A related tract (Nardone et. al, 2020).

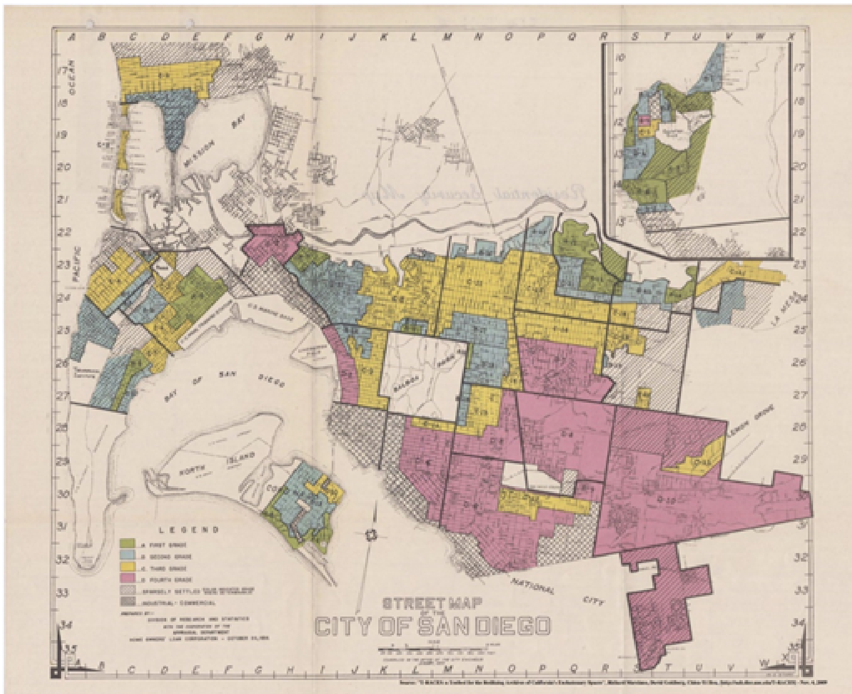

Figure 2: Map of the City of San Diego from 1936 created by HOLC. The level D regions (red) were considered the highest risk for mortgage default (T-Races, 2018).

Overall, redlining resulted in racial segregation and decreased home values (Nardone et. al, 2020). Besides redlining, there was also racial zoning and eminent domain; these policies led to the placement of schools, highways, and toxic-hazard sites (Nardone et. al, 2020). Marginalized communities still live in these segregated neighborhoods and hazardous sites and tend to have higher levels of unemployment, poverty, and industrial pollution (Bailey et al., 2017; Nardone et. al, 2020).

Communities of color in the United States continue to be disproportionately exposed to outdoor air pollution, which in turn leads to health disparities (Chakraborty, 2020). The most affected communities are the non-Hispanic Black population, adults without high school education, and people living in poverty (Chakraborty, 2020). Furthermore, African Americans and Hispanics have higher levels of exposure to air pollution while contributing to pollution much less than other populations (Chakraborty, 2020). In the United States, 11% to 19% of the population live within a few hundred meters of major roads, with more than 40 million people being exposed to high levels of $PM_{2.5}$ (Askariyeh et al., 2020). Roads and vehicles can influence marginalized communities significantly. In California, the African American, Latino, and Asian populations are exposed to traffic-related $PM_{2.5}$ in a greater proportion (43%, 39%, and 21% higher, respectively) than the white population (Reichmuth, 2019). Low-income individuals in California live where $PM_{2.5}$ pollution is 10% higher than the state average, whereas high income individuals live where $PM_{2.5}$ pollution is 13% below the state average (Reichmuth, 2019). Therefore, different communities have different exposures to traffic-related $PM_{2.5}$.

Reductions of TRAP may significantly influence marginalized communities exposure to $PM_{2.5.}$. Therefore, there needs to be policies that address these health disparities and inequality by drastically decreasing traffic related $PM_{2.5}$. This is a difficult challenge from the federal level to the local level (i.e., cities). However, the coronavirus (COVID-19) pandemic drastically reduced TRAP (Cicala et al., 2020). As a result, policymakers have a unique opportunity to study this short-term decrease in TRAP (Gkatzelis et al., 2021).

1.4. COVID-19 Policies

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a virus that becomes a respiratory disease known as COVID-19. On March 11, 2020, WHO announced COVID-19 as a pandemic (The City of San Diego, 2020). To stop the spread of the disease, governments implemented different restrictions and policies to protect public health. As a result, there were lockdowns globally, which occurred mainly from March to May in the United States (Venter et al., 2020). Lockdowns included policy restrictions such as stay-at-home orders, mask mandates, shutdown of many businesses, social distance, and among others (Venter et al., 2020).

Due to the temporary closure of businesses and switching to virtual platforms, many industries have limited their in-person operations (Madurai et al., 2020). As a result of these policies and lockdowns, economic activity associated with transport and population mobility decreased significantly in many countries (Venter et al., 2020). Based on cellular phone data, vehicle miles traveled (VMT) dropped about 41% in the United States, with a 42.7% decrease in California and 51.6% in San Diego County from March to mid-April 2020 (Cicala et al., 2020).

Air pollution levels, mainly NO_2 and $PM_{2.5}$, have decreased in many cities due to the decline of the transportation sector (Liu et al., 2020; Venter et al., 2020). During the lockdown period in California, (March 19-May 17) a 31% decrease in $PM_{2.5}$ concentrations was observed (Liu et al., 2020). When the lockdown restrictions were loosened in May 2020, economic activity in the transportation sector increased; as a result, global $PM_{2.5}$ increased and returned to normal levels after 2 months (Venter et al., 2020). In California, $PM_{2.5}$ and PM_{10} increased by 17% and 14% once economic and transport activities resumed around mid-May 2020 (Liu et al., 2020) **.**

COVID-19 policies resulting in a reduction of economic activity and mobility provide a natural experiment to study the impact of air pollution emissions, particularly at the regional scale (Gkatzelis et al., 2021). Overall, air pollution decreased for a short period of time, which resulted in good air quality in many regions in the world (Venter et al., 2020). However, the environmental (in)justice implications at the small-scale level were not explored.

2. Research Question and Objectives

Objective 1: To assess and quantify any changes in $PM_{2.5}$ in San Diego County during the different stages of COVID-19-related restrictions in 2020.

Objective 2: To describe the relationship between changes in $PM_{2.5}$ and socioeconomic status (SES) indicators across ZIP codes in the county.

Therefore, the main question is

Were the benefits of the COVID-19-related policies (e.g, stay-at-home order) and changes in $PM_{2.5}$ levels distributed equally across ZIP codes in San Diego county?

3. Methods

3.1. $PM_{2.5}$ Anomalies

The study area comprised 98 ZIP codes in San Diego County. In order to quantify changes in PM2.5 in 2020, anomalies (i.e., deviation from the "expected" value) were estimated for each ZIP code using historical data (years 2000-2019). Specifically, PM2.5 anomalies were calculated by estimating the daily ZIP code-specific concentrations of PM2.5 from 2000 to 2020, using 24-hour daily means sampled and analyzed by the US EPA Air Quality System (https://www.epa.gov/aqs) at ground monitoring stations. PM2.5 anomalies were calculated by subtracting the weekly average of PM2.5 concentrations per ZIP code in 2020 by the weekly weighted average of PM2.5 concentrations per ZIP code from 2000 to 2019. A weighted average was calculated since the recent years have more of an influence on estimating counterfactual values for current PM2.5 levels than the earlier years. The moving average for the weekly PM2.5 anomalies was also calculated to attain the overall trend. The moving average was conducted by taking the average of PM2.5 levels within two weeks before and two weeks after a certain week in the historical period (2000-2019). PM2.5 anomalies were calculated by means of Excel spreadsheets and the Matlab software (MATLAB, 2020). ArcGIS (Esri Inc., 2020) was used to map the spatial variability in PM2.5 anomalies throughout the county. Negative PM2.5 anomalies would indicate a decrease in concentrations on a given week in 2020 (as compared to a counterfactual situation where COVID-19 lockdown would not take place) with respect to the PM2.5 concentrations during the historical period. Positive anomalies, on the other hand, indicate an increase in PM2.5 levels.

In San Diego County, several policies and measures have been taken to combat the spread of COVID-19 (**Table 1**). Weekly values of $PM_{2.5}$ anomalies were grouped based on the different COVID-19 policies that took place in 2020. Overall, five different periods were considered (**Table 1**). Analysis #1 is related to the first stay-at-home order (weeks 11 to 20). Analysis #2 is the shutdown of indoor activities during the summer (week 29 to week 34). This is known as the summer restrictions for simplicity. Analysis #3 is the second stay-at-home policy (weeks 47 to 53). Analysis #4 is the combination of analysis #1, #2, and #3. Therefore, analysis #4 is the average of the lockdown weeks for each ZIP code during 2020. Analysis #5 is the wildfire season since wildfires can influence $PM_{2.5}$ concentrations significantly (weeks 36 to 45).

3.2. COVID-19 Policies

Dates	Weeks	Policies	Details
February 19th	8	Local Health Emergency (San Diego County)	The County of San Diego Board of Supervisors declare of Local Health Emergency
March 12th (Analysis #1 and #4)	11	Stay at Home in San Diego County)	The Public Health Order focuses on the use of face coverings, prohibits gatherings, and orders the residents to stay at their homes excluding traveling for essential businesses
March 19th (Analysis #1 and #4)	12	Stay at Home Order (California)	Governor Newsom ordered a Stay at Home Order that required California residents to stay at home except for essential activities
May 18th	21	Reopening parameters changed	Governor Newsom changed reopening parameters by easing the state guidelines
June 12th	24	Some businesses reopen	Some indoor businesses such as restaurants, gyms, and retail stores can reopen if they meet the state guidelines
July 13th (Analysis #2 and #4)	28	Many indoor activities closed - summer restrictions	The State of California ordered the closure of indoor activities for the industries and activities within certain counties including San Diego county such as restaurants, personal care services, etc.

August 28th	35	Blueprint for a Safer Economy (California)	Governor Newsom announced that certain businesses and activities can reopen
November 21st (Analysis #3 and #4)	47	Limited Stay at Home Order - Second Stay at Home Order (California)	This order was ordered in counties in the purple tier to stop non-essential activities between 10 p.m. and 5 a.m.
December 21th (Analysis #3 and #4)	52	Regional Stay Home Order Continues (California)	Regional Stay Home Order ordered counties with low ICU capacity to stop non-essential businesses between 10 pm to 5 am

Table 1: COVID-19 policies and measures in San Diego County (The City of San Diego, 2020; Proctor, 2020).

3.3. Wildfires

In the beginning of September 2020 (week 36), there were two major fires that burned more than 10,000 acres in neighboring Riverside and San Bernardino counties (i.e. El Dorado Fire). That same week, a major fire in inland San Diego County, the Valley Fire, burned 16,390 acres and was officially contained on September 24th, 2020 (https://www.fire.ca.gov/incidents/2020/). At the end of October, there were two big fires in Orange County (https://www.fire.ca.gov/incidents/2020/). The Silverado and Blue Ridge Fires started on October 26th and ended on November 7th, 2020. The Silverado Fire burned 12,466 acres whereas the Blue Ridge Fire burned 13,964 acres.

3.4. Socioeconomic Status (SES) Variables

Seven socioeconomic status (SES) variables were considered in this study based on previous evidence documenting inequalities in exposure to air pollution according to these metrics: unemployment rate, education (less than high school education), housing units, percentage of Latino Hispanics population, percentage of Black African Americans population, median household income, and percentage of below poverty level obtained from American Community Survey (ACS, 2019).

3.5. Statistical Analysis

Linear regressions were used to quantify the association between each SES variable and PM2.5 anomalies during each period (Analyses #1-5; Table 1). The slope and 95% confidence intervals were calculated to represent the association between PM2.5 anomalies and each SES variable.

4. Results

4.1. Weekly $PM_{2.5}$ Anomalies in San Diego County

First, on February 19th, San Diego county declared a local health emergency (week 8). On March 12th (week 10), the city of San Diego recommended residents to stay at home (The City of San Diego, 2020). On March 19th, there was a statewide stay-at-home order (Procter, 2021). As a result, high negative $PM_{2.5}$ anomalies were mainly observed from week 10 to week 15 (**Figure 3)**. Throughout April, due to decreasing cases of COVID-19 hospitalizations, restrictions began to loosen and positive anomalies in PM2.5 concentrations emerged. The highest positive $PM_{2.5}$ anomalies were observed from weeks 35 to 44 (shaded area in **Fig. 3**) mainly due to wildfires burning in the region. In addition, On August 28th, week 35, Governor Newsom announced the "Blueprint for a Safer Economy, " which allowed the reopening of certain businesses and activities (The City of San Diego, 2020). On November 21st (week 47), the second stay-at-home order, "Limited Stay at Home," was announced due to many counties being in the purple tier (high COVID-19 cases) in the beginning of November. During this period, PM2.5 levels started to slightly decrease again. The maps in Figure 4 display average $PM_{2.5}$ anomalies for each of the five analyses considered, based on 2020 restrictions.

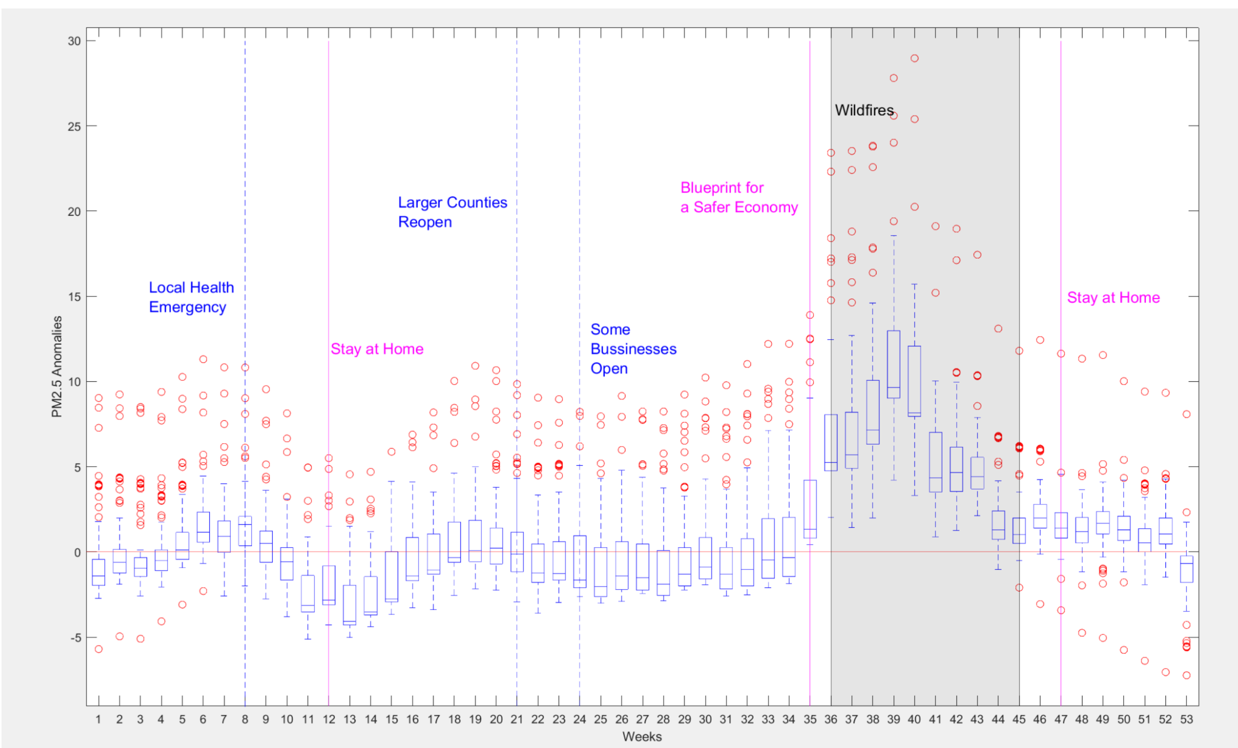

Figure 3: $PM_{2.5}$ anomalies throughout 2020 (53 weeks), with respect to the historical period (2000 - 2019). Below the zero mark (red horizontal line), negative anomalies represent a decrease in $PM_{2.5}$ during 2020, whereas positive anomalies indicate an increase in $PM_{2.5}$ concentrations. The vertical lines represent the different COVID-19 policies that occurred at a given week.

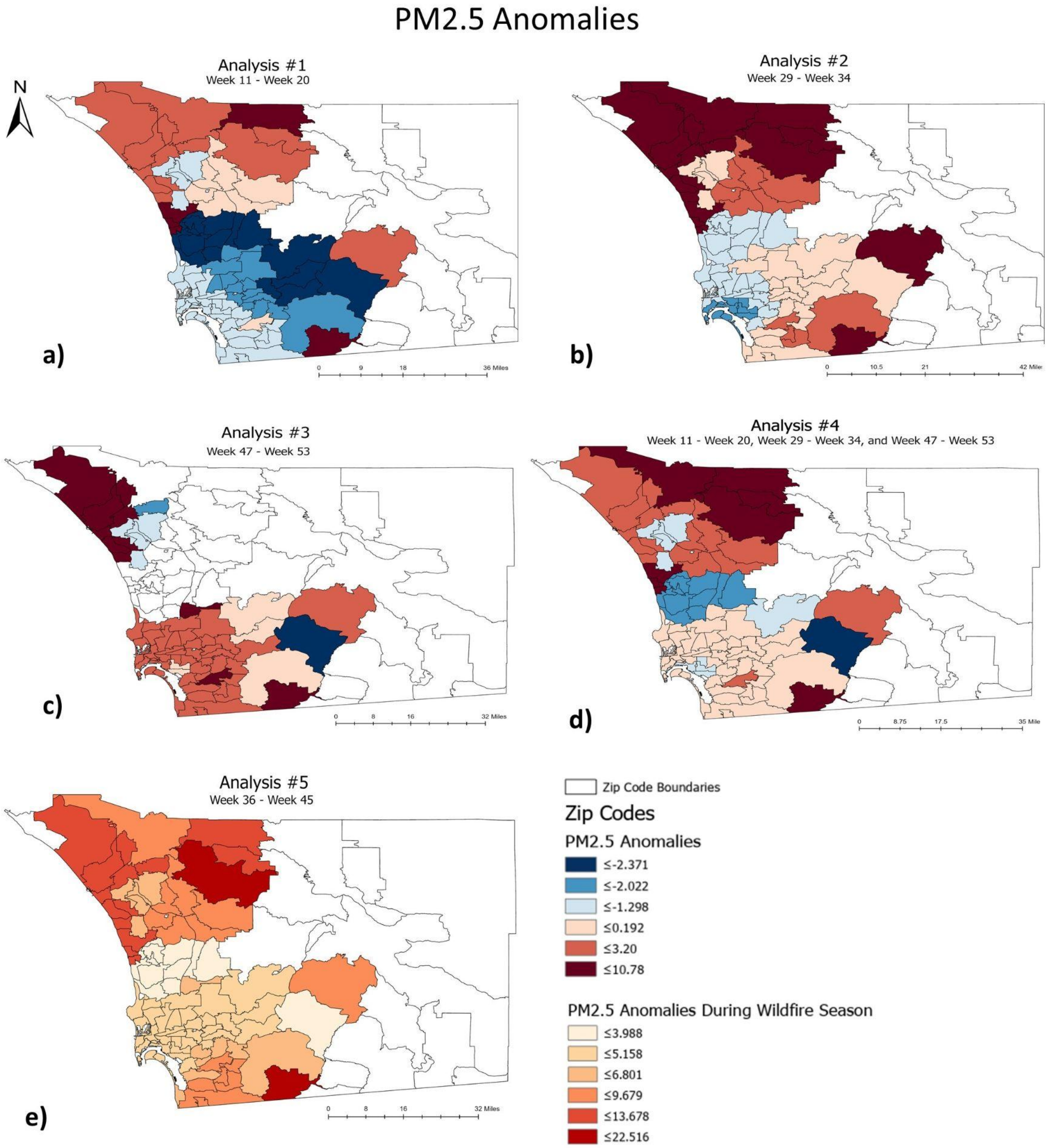

Figure 4: These are the $PM_{2.5}$ anomalies in San Diego County. **a)** is during the first stay-at-home order from week 11 to week 20. **b)** is during the summer restrictions from week 29 to week 34 (July to August 2020). **c)** is during the second stay at home order from week 47 to week 53 (November 2020 to January 2021). **d)** during all of the lockdowns of 2020 including March to May 2020, July to August 2020, and November to January 2021. Red shades represent positive $PM_{2.5}$ anomalies while the blue shades represent negative $PM_{2.5}$ anomalies. **e)** is during the wildfire season from week 36 to week 45 (September 2020 to the beginning of November 2020).

South San Diego County, including downtown San Diego, displayed negative $PM_{2.5}$ anomalies ranging from -2.371 to -1.298 (**Figure 4a**). Central San Diego County has the largest negative anomalies, which means that $PM_{2.5}$ levels were lower than usual. The north coast of San Diego County is associated with positive anomalies (3.20 and 10.78) meaning the $PM_{2.5}$ levels were higher than the historical period (**Figure 4a**). Overall, the majority of ZIP codes in San Diego County showed negative anomalies during the first stay-at-home order in March-May 2020.

Positive anomalies (0.192 to 10.782) were observed in the northern and southern ZIP codes during weeks 29-34 (**Figure 4b**), which means the $PM_{2.5}$ levels were higher than the historical record for those weeks. ZIP codes in inland San Diego County also showed $PM_{2.5}$ values much higher than the expected levels based on the historical period. There was missing data in some ZIP codes during the period within weeks 47-53 (**Figure 4c**). Here, the majority of the county recorded positive anomalies, with $PM_{2.5}$ levels higher than usual for that time of year. The average of $PM_{2.5}$ anomalies during Analyses #1-3 is shown in Figure 4d (Analysis #4), with most northern and southern ZIP codes having positive PM2.5 anomalies. During the weeks affected by wildfire smoke (Analysis #5; **Figure 4e**), all ZIP codes showed positive anomalies, meaning the $PM_{2.5}$ levels were higher than usual.

4.2. Spatial Patterns in Socioeconomic Status (SES) across the County

The following maps (**Figure 5**) display the spatial distribution of each individual SES variable. ZIP codes in South San Diego County have the highest percentage of Hispanic Latino population, ranging from 38.3% to 94.4% (**Figure 5e**). This region also has the highest number of total housing units, particularly near the border with Mexico (**Figure 7 in Appendix**). Figure 5c shows that inland San Diego County and ZIP codes close to the international border have the highest rates of poverty, ranging mainly from 13.5% to 30.1% of the population living under these poverty conditions. In addition, this southern area of San Diego County has a higher unemployment rate (ranging from 7.5% to 12.2% of the population being unemployed; **Figure 5a**). Inland ZIP codes also show a high unemployment rate, ranging from 5.3% to 19.6%.

Areas in San Diego County with the highest income are found near Del Mar and La Jolla (north), whereas the southern part of the County (mainly near the border with Mexico) has the lowest income. The lowest percentage of the population that has attained higher education is found in San Diego city (e.g., Logan Heights), as well as inland ZIP codes in the County (**Figure 5d**).

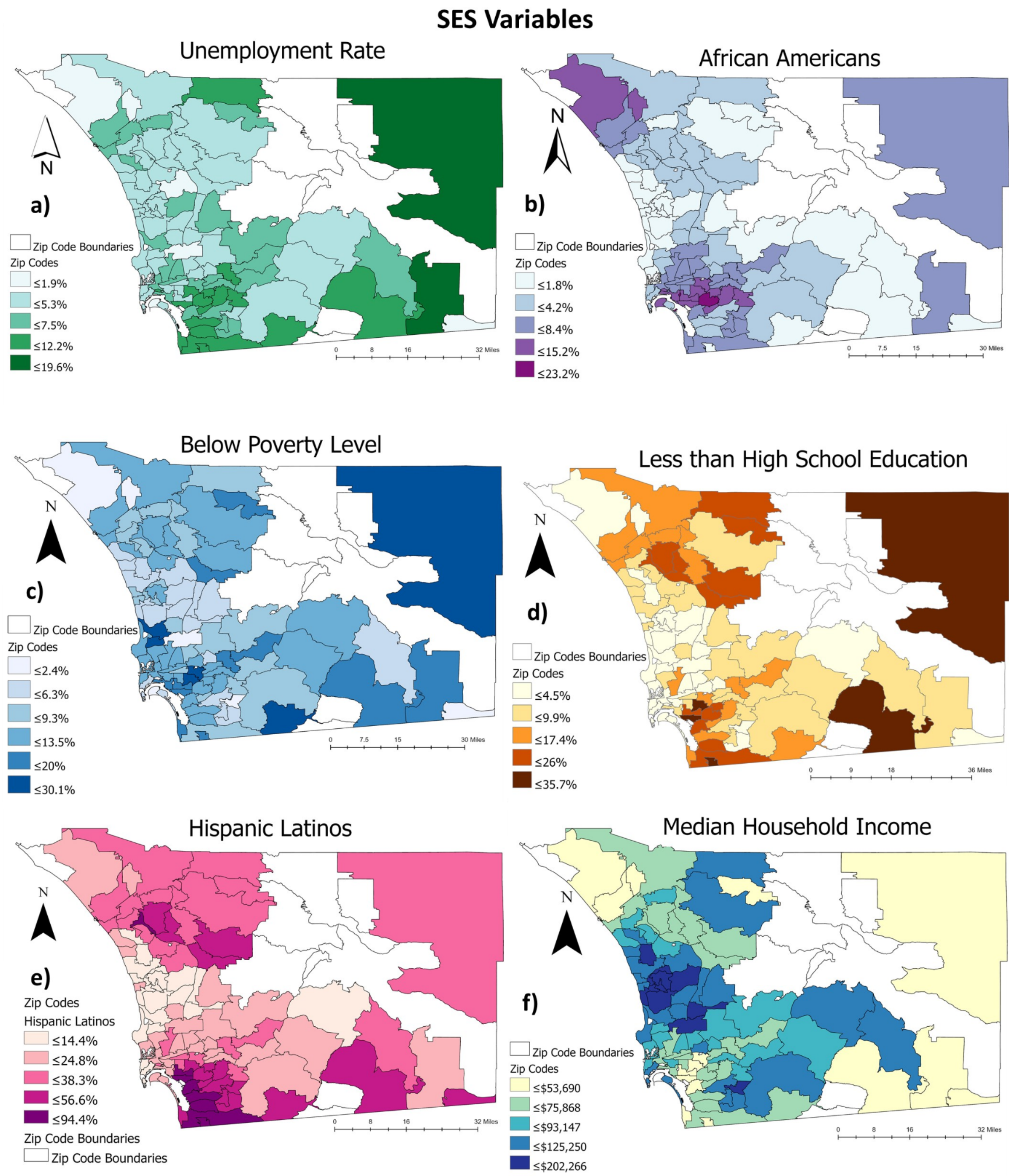

Figure 5: This is the spatial variability of the SES variables across San Diego County. **a)** shows the spatial variability of the rate of unemployment. **b)** spatial variability of percentage of African American population. **c)** shows the spatial variability of the rate of the population that are below the poverty **d)** percentage of the population that has a high school diploma and less. **e)** percentage of Hispanic Latinos within each zip code. **f)** shows the median household income variables.

4.3. Association between $PM_{2.5}$ anomalies and SES in San Diego County

Most SES indicators did not have a detected relationship with PM2.5 anomalies in the five analysis periods considered. However, we found a negative relationship was observed between the percentage of the population with higher education and PM2.5 anomalies during Analyses #2 and #5. In addition, the number of housing units was inversely related to PM2.5 anomalies. The percentage of African Americans living in a given ZIP code was inversely related to PM2.5 anomalies in all analyses with the exception of #3 (**Table 2; Figure 6**). The rest of SES variables cross the vertical line (0 mark; **Figure 6**); which indicates no detected correlation. Therefore, they do not have a linear relationship with PM2.5 anomalies that can be captured by the regression analysis.

SES Variable	Analysis #1 Slope (95% CI)	Analysis #2 Slope (95%CI)	Analysis #3 Slope(95%C)	Analysis #4 Slope (95% CI)	Analysis #5 Slope (95% CI)
% Poverty	1.47 (-7.15, 10.1)	2.33 (-9.41, 14.09)	4.59 (-3.26, 12.58)	2.29 (-6.72, 11.16)	3.74 (-9.06, 16.55)
% Education	$-6.20x10^{-5}$(-10.71, 5.14)	$-8.72x10^{-5}$ (-15.58, -1.33)	$-2.32x10^{-5}$(-3.53, 6.82)	$-6.17x10^{-5}$(-8.98, 2.22)	-5.59 (-13.52, 2.33)
% Unemployment	2.71 (-15.49, 20.92)	12.29 (-12.55, 37.12)	7.73 (-9.58, 23.97)	6.036 (-12.98, 24.72)	15.10 (-12.02, 42.21)
Income	$-4.50x10^{-6}$ ($-2.15x10^{-5}$, $1.24x10^{-5}$)	$-3.14x10^{-6}$ ($-2.56x10^{-5}$, $1.93x10^{-5}$)	$6.54x10^{-6}$ ($1.2x10^{-5}$, $2.63x10^{-5}$)	$-6.21x10^{-6}$ ($-2.34x10^{-5}$, $1.18x10^{-5}$)	$-1.10x10^{-5}$ ($3.6x10^{-5}$, $1.39x10^{-5}$)
% African Americans	-15.35 (-25.50, -5.20)	-23.70 (-33.10, -14.29)	-3.862 (-12.56, 7.07)	-13.38 (-24.61, -3.29)	-18.55 (-33.75, -3.36)

% Hispanic Latinos	-0.654 (-3.36, 2.05)	-0.401 (-4.09, 3.28)	-0.011 (-2.71, 2.50)	-0.089 (-2.98, 2.63)	3.13 (-0.84, 7.09)
Housing Units	-9.03×10^{-5} (-1.50×10^{-4}, -3.08×10^{-5})	-0.00014 (-2.16×10^{-4}, -5.58×10^{-5})	-3.2×10^{-5} (-8.92×10^{-5}, -3.2×10^{-5})	-9.02×10^{-5} (-1.54×10^{-4}, -3.07×10^{-5})	-0.00011 (-2×10^{-4}, -2.08×10^{-5})

Table 2: Linear regression slope values and 95% confidence intervals (CI) between each SES variable and PM2.5 anomalies for all analyses.

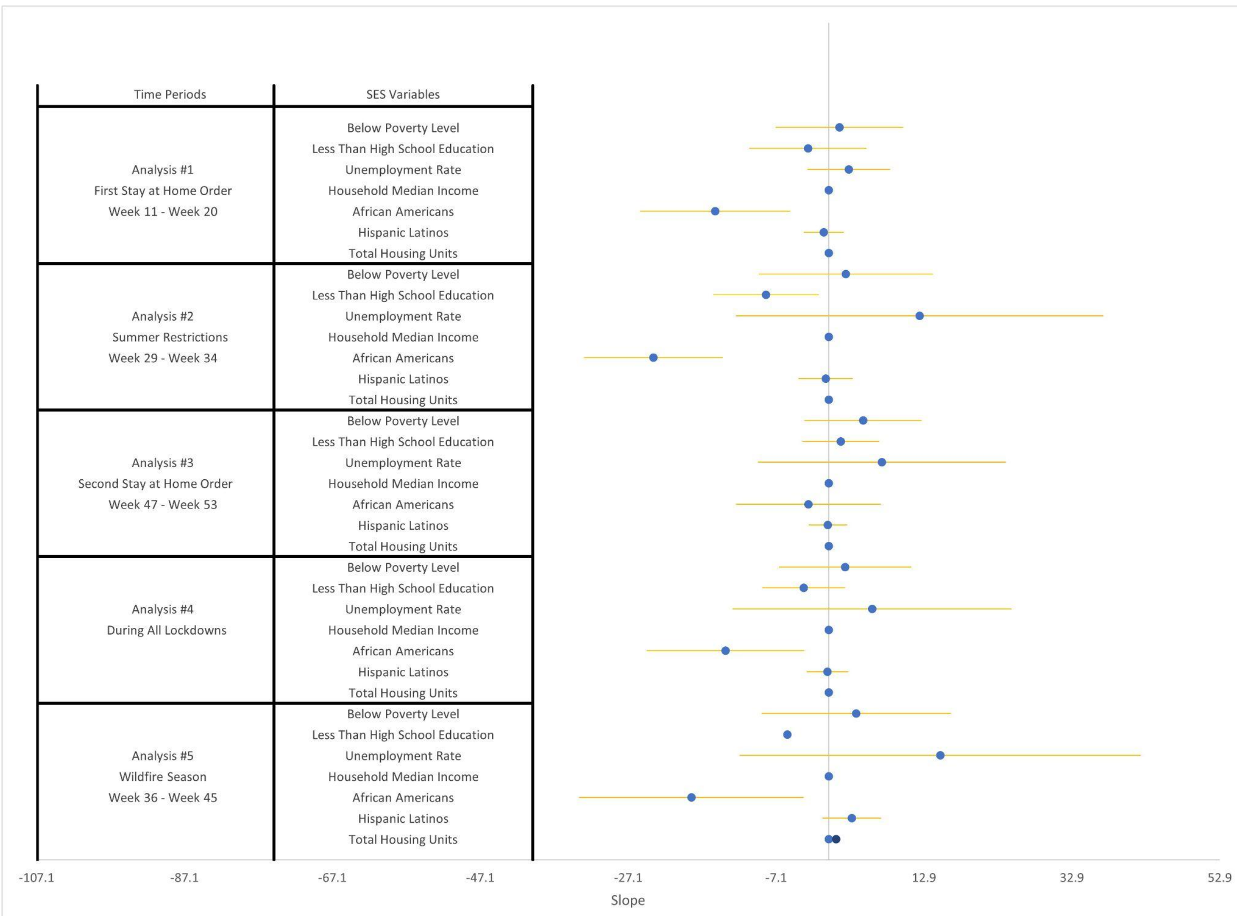

Figure 6: This figure shows a summary of the linear regression results such as the slope (blue points) and the 95% CI (horizontal lines) for all SES variables in each analysis. The first column lists the time periods, and the second column lists the SES variables.

5. Discussion

The period comprised in Analysis #1 showed the highest number of ZIP codes with negative PM2.5 anomalies (**Figure 4a**), potentially as a result of decreased population mobility and economic activity during the first stay-at-home order. In contrast, the other analyses mainly showed positive anomalies across ZIP codes in the County. Analysis #2 and #3 followed the period of the first stay-at-home order. The summer restrictions (analysis #2) were only for a short period of time and much less strict than in Analysis #1. The second stay-at-home order (analysis #3) was during the November-December holiday period; when people seemed to have spent time with their families in spite of social distancing recommendations. Overall, PM2.5 pollution decreased the most during the first stay at home order (analysis #1) around mid-March, 2020.

South San Diego mostly showed positive PM2.5 anomalies in all periods evaluated, with the exception of analysis #1 (**Figure 4a**). Overall, not all ZIP codes experienced the same PM2.5 levels. Some areas in the County had better air quality (negative PM2.5 anomalies) for a short period of time (e.g., weeks 10-15), whereas other areas had much higher levels of PM2.5 when compared to the 20-year historical record averages. These highest levels of PM2.5 anomalies were mainly associated with weeks affected by wildfire smoke. For instance, at the start of Analysis #5 (week 36; September 2020), there were major fires that burned more than 10,000 acres in San Diego County (e.g., Valley Fire), as well in the neighboring Riverside and San Bernardino counties (https://www.fire.ca.gov/incidents/2020/). In addition, there were two large fires in Orange County (Silverado and Blue Ridge Fires; https://www.fire.ca.gov/incidents/2020/). All of the above fires burned more than 10,000 acres and were near or within San Diego County, exposing the population to high PM2.5 concentrations in wildfire smoke.

Regarding the indicators related to SES, ZIP codes in South San Diego County seem to be the most disadvantaged in terms of low income, high unemployment rate, higher below poverty rate and less education. In this same area, there is a higher percentage of Hispanic Latino inhabitants (38.3% to 94.4%), as well as African Americans (8.4% to 15.2%) (**Figure 5**). The regression analyses showed an inverse relationship between the percentage of African American population and PM2.5 anomalies. The opposite would have been expected, where a direct (positive slope) relationship would indicate a higher prevalence in PM2.5 pollution in ZIP codes with the highest percentage of marginalized communities, such as African Americans, living. It is worth mentioning that the highest percentage of this population is below 25%, which means there are not many African American individuals in San Diego County. The rate of unemployment was positively related to PM2.5 anomalies, as well as the indicator for the population living below poverty level. As expected, areas with higher levels of poverty and unemployment tend to be associated with higher levels of air pollution, due to pervasive environmental inequities.

6. Policy Recommendations

Due to measures taken during the COVID-19 pandemic, many citizens had to stay at home, which decreased both economic activities and population mobility (Venter et al., 2020). This resulted in a decline in air pollution levels in some regions worldwide. However, the decrease in air pollution could just be attributed to meteorology factors (weather, wind, etc.), traffic patterns, and time of day (ARB, 2017). In addition, this decrease was only short-term.

After the stay-at-home policy, PM2.5 levels went up as industry and transportation activities resumed (Venter et al., 2020). Society needs to search for long-term solutions by shifting towards sustainable and innovative methods such as making public transportation accessible and using electric cars. This pandemic serves as a natural experiment of an intervention, such as decreased mobility and traffic, that can further inform policymakers, governmental officials, and stakeholders about patterns in air pollution and their links to environmental justice. Based on the conclusions drawn from the pandemic and its impacts on economic activity and traffic related to population mobility, the main policy goal for reducing air pollution and exposure is to minimize traffic pollution, which involves reducing vehicle miles traveled (VMT; ARB, 2017).

6.1. Stricter Policies

As mentioned before, air pollution policies mainly focus on compliance of environmental thresholds for pollutants but not necessarily on mitigating the impacts of emissions (Environmental Defense Fund, 2020). Existing policies have helped to improve fuel efficiency and reduce emissions in newer vehicles (Environmental Defense Fund, 2020). However, there are still high traffic emissions near roadways, which detrimentally affects human health (ARB, 2017). Therefore, cutting emissions at the source will be more beneficial for protecting people's health in the long run (Environmental Defense Fund, 2020). For instance, it is recommended to reduce VMT, which leads to a clear decrease in air pollution (Tanzer-Gruencer et al., 2020). Hence, there needs to be more strict emission regulations and fuel standards for trucks, buses, and cars (ARB, 2017). For example, the most recent policy recommendation is changing the annual PM2.5 NAAQS to as low as 9 $\mu g/m^3$ (Tanzer-Gruencer et al., 2020). If this occurs it is estimated that the PM2.5 related mortality rate will decrease by 21-27% (Tanzer-Gruencer et al., 2020). Moreover, in California, there are state regulations for zero emission vehicles (ZEV) adoption (ARB, 2017). Overall, it is a challenge for air quality agencies to reduce emissions per VMT. Therefore, there should be other strategies to reduce TRAP and VMT.

6.2. Technology

Technologies that minimize air pollution by replacing diesel and gasoline vehicles with natural gas, hybrid, or all electric vehicles, can lower local transportation emissions (Winer, 2008; Reichmuth, 2019). These measures can also aid in increasing fuel efficiency, emitting less VMT, and identifying super emitters. For example, at a state level, California should consider adoption of such technologies that support Smog Check and "buy and crush " strategies (ARB, 2017). This strategy involves Smog Check programs requiring the oldest vehicles to get checked in order to avoid circulation of super emitters, or highly polluting vehicles (Winer, 2008). Having these technologies can reduce air pollution and carbon emissions, which can address the inequity of PM2.5 exposure (Reichmuth, 2019). In addition to reducing traffic and air pollution, a long-term solution, involving changes in mobility behavior of our society, is needed to provide further significant reduction in emissions.

6.3. Alternatives

Cities should encourage other forms of transportation besides driving a personal vehicle. For instance, biking, walking, carpooling, teleworking, and using public transportation can decrease air pollution (UCAR, 2020). Therefore, policymakers should focus on shifting towards more sustainable options such as improving and encouraging the use of public transportation (Sung and Monschauer, 2020). However, there needs to be proper infrastructure to make these sustainable options accessible and possible (Sung and Monschauer, 2020). Urban planning strategies such as transportation, smart growth and land-use strategies could help reduce VMT and associated emission in the long term (Winer, 2008).

6.4. Urban Planning

Urban planning should involve sustainable measures such as supporting public transportation. One component of sustainable planning is implementing smart growth, which involves creating compact neighborhoods (high density development and efficient use of land), having residential housing near work and services, increasing access to mass transit, and reducing usage of automobiles (Wheeler, 2013; Winer, 2008). Therefore, implementing smart growth in urban planning strategies can reduce automobile trips to the city, which leads to a reduction in VMT. Focusing on infill development (i.e., redeveloping vacant lots or underutilized lands in urban areas) can support sustainable communities by protecting the environment, promoting equity, and promoting public health and safety (Wheeler, 2013; ARB, 2017). For instance, designing and creating sustainable land use (compact, balanced, and mixed-use communities) can support other forms of transportation, which can promote community connection (Wheeler, 2013; ARB, 2017). Overall, these changes can help reduce VMT by making transit and active transportation accessible and thus reducing the need for personal cars (ARB, 2017).

It is important to consider the location of residential housing in urban planning and avoid developing housing within proximity to freeways. Street, highway, and freeway ramp intersections have been found to be air pollution hot spots in most urban regions, and it is also the case in California (ARB, 2017). Another important consideration in urban planning is vegetation and green spaces, which can possibly change pollutant transport and dispersion (ARB, 2017). For example, there are measured reductions of PM within or near urban parks and forests (ARB, 2017), since trees can reduce ambient pollutant concentrations by increasing turbulence (ARB, 2017) and removing air pollutants from the atmosphere.

6.5. Community Advocacy

First, public authorities and policymakers need to inform marginalized communities on the disproportionate effects of air pollution on their health (Mitchell et al., 2015). In addition, public authorities can support these communities in fighting for environmental justice, racial justice, and health equity (Wilson, 2020). For example, participatory research can play a role in educating the community by connecting community knowledge, scientific research, and community action together (Wier et al., 2009). Next, environmental injustice cannot be tackled only at the local (i.e., community) level; it requires engagement at the federal and state levels (Mitchell et al., 2015). This may be challenging for environmental justice activists since they are mainly familiar with dealing with local problems (Mitchell et al., 2015). Overall, environmental justice activists argue for having an inclusive and deliberative decision-making process that involves these impacted communities' inputs on tackling air quality problems, providing scientific information, setting better standards (Mitchell et al., 2015).

7. Conclusion

Overall, I aimed to assess the impacts of COVID-19 mobility restrictions on PM2.5 concentrations across all ZIP codes in San Diego County. In addition, I aimed to assess any environmental justice implications of the observed changes in PM2.5 pollution in the year 2020. During the first stay-at-home order (analysis #1), there were mainly negative PM2.5 anomalies across the county, which implied a decrease in PM2.5 pollution with respect to the same weeks in the historical period (2000-2019) for most ZIP codes. However, with the subsequent restrictions (analysis #2 and #3), PM2.5 anomalies were not as low. South San Diego County was the most disadvantaged area with a high unemployment rate, a low income, a high poverty rate, and low formal education. This area consists of a higher percentage of Hispanic Latinos and African Americans. COVID-19 mobility restrictions and the associated short-lived decline in air pollution influenced the ZIP codes differently. The SES indicator for percentage of African American inhabitants had an inverse relationship with PM2.5 anomalies, which suggests a decline of this type of pollution in areas where most African Americans live. Therefore, this is a positive finding. Nevertheless, policies that account for health disparities are needed to tackle the inequity in environmental impacts across San Diego County. This includes stringent policies, urban planning accounting for a better transit system, community advocacy, and cleaner technology.

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APPENDIX

SES Variables

1.Total Housing Units

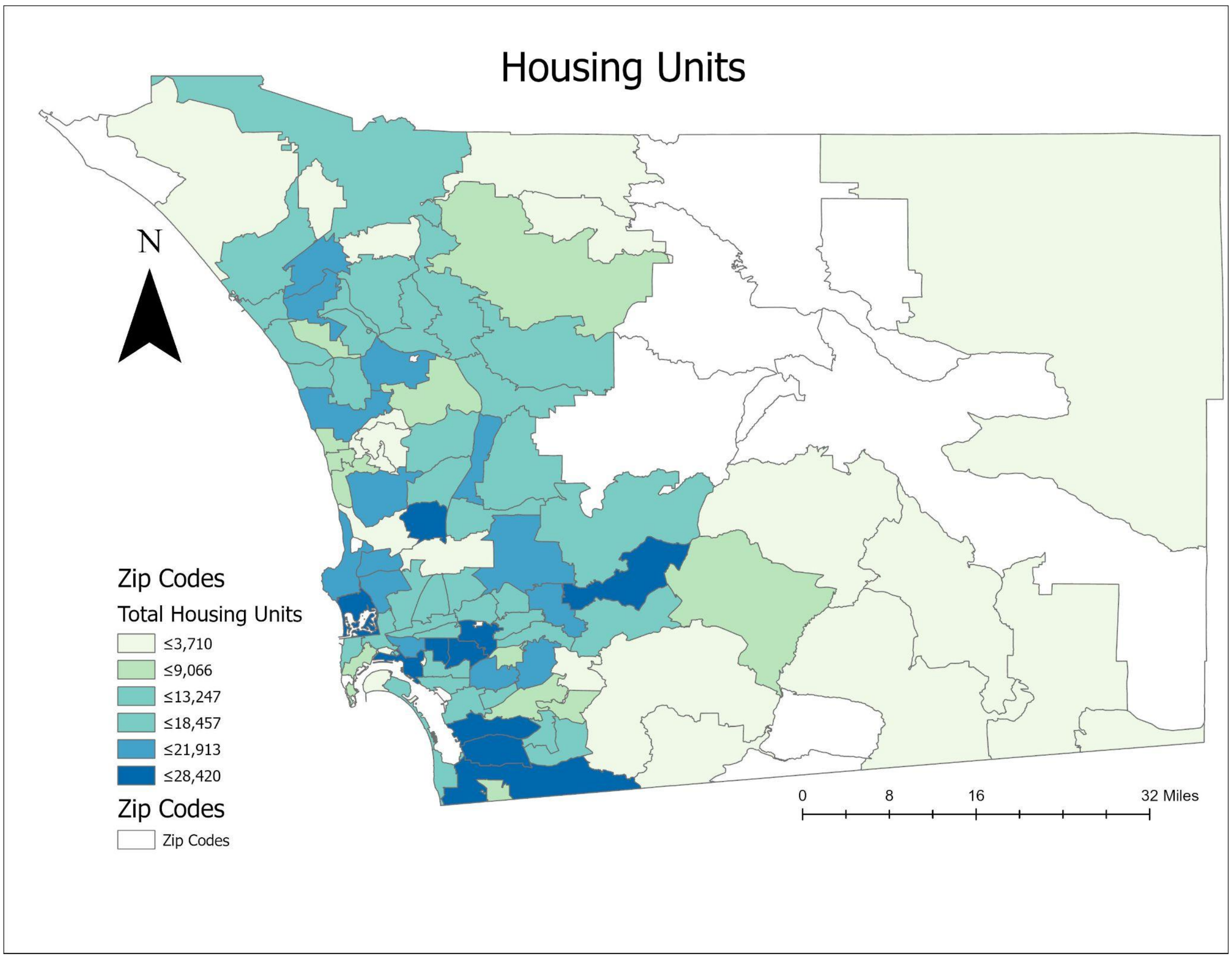

Figure 7: This is the spatial variability of the Housing Units variable across San Diego County. This SES variable focuses on the number of housing units within each zip code. The highest number is dark blue (28,440) and the lowest income is light green (3,710).