Spatio-temporal analysis of COVID-19's impact on human mobility in NYC

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1 Introduction

Since the World Health Organization declared the novel coronavirus (COVID-19) outbreak a global pandemic on March 11 2020, the disease has influenced every part of people's daily life and caused more than six million deaths globally (Johns Hopkins Coronavirus Resource Center, 2022). Mobility pattern tracks human movement behavior. It is critical to understand, evaluate and predict the pandemic transmission. Commuting and large-scale gathering aggravate pandemic transmission, at the same time the pandemic transmission prevents social activity and lowers travel behavior. Thus, many non-pharmacological policies such as quarantines, travel restriction, social distancing have been implemented by governments to prevent the spread of COVID-19.

As the most populous city in the United States with 8.8 million people distributed over 300.46 square miles (U.S Census Bureau, 2020), New York City has experienced rapid and widespread transmission since the first confirmed case on March 1st 2020. At the end of March 2020, NYC arrived at the peak of COVID-19 and became the pandemic epicenter (Cordes & Castro, 2020) with a weekly mean of 5, 132 diagnosed cases and 1,566 hospital admissions. On March 22, 2020, 'New York State on PAUSE' executive order was declared. It includes a new directive that all non-essential businesses statewide must close in-office personnel functions effective (New York State Office, 2020). Identifying the spatio-temporal changes of human mobility pattern before, during and after the outbreak of COVID-19 is important to analyze COVID-19's impact on individuals. In addition, analyzing mobility changes under the contextual backgrounds suggests the heterogeneity of COVID-19's impacts on different groups. For example, high-income individuals may choose to decrease their visits to wholesale markets and restaurants and buy takeaways services to access necessary foods. However, people with low- or moderate- incomes may have no choice but to leave home to buy food with higher risk of infection.

Therefore, the objective of this paper is to study the spatio-temporal changes of mobility pattern in NYC in March 2019, March 2020 and March 2021 and analyze the social equity issues caused by the pandemic. The research is aimed to answer the following questions:

1. What is the spatial shifting pattern of visit counts to different business categories?
2. What is the temporal change of mobility pattern before, during and after COVID-19?
3. How does COVID-19 influence individual's travel behaviors in different contexts?

2 Data

The mobility information is provided by the pattern datasets and core place dataset from SafeGraph. SafeGraph is a data company that aggregates anonymized individual location data at point of interests (POI) level from third-party applications. Pattern dataset records count of visit, vistor and thier duration time at different POI. There are 419, 742 devices captured in New York's mobility pattern dataset, which covers 25% of total census population in New York approximately. Core place dataset are defined as any location humans can visit with the exception of single-family homes. There are 84, 717 POI recorded in Core place dataset, which encompasses a diverse set of places ranging from restaurants, grocery stores, and malls; to parks, hospitals, museums, offices, and industrial parks (SafeGraph, 2022).

However, the datasets from SafeGraph does not cover all actual visitors but rather a subset of users that have smartphones and enabled their GPS information in various apps (Sevtsuk, 2021).

Socio-economic information such as race and income is from the American Community Survey (ACS) 2015-2019 5-year data.

The geographic base map of NYC is US Census Bureau's TIGER 2020 Census Tracts (clipped to shoreline) data products.

Data	Geographic Level	Source
Mobility Pattern in March **2019**	Block Group	SafeGraph
Mobility Pattern in March **2020**	Block Group	SafeGraph
Mobility Pattern in March **2021**	Block Group	SafeGraph
Core Place	Block Group	Block Group
Demographic Data (e.g. income, race)	Census Tract	ACS 2019 5-year data
Geographic boundary	Census Tract	US Census Bureau

Table 1: Data source

3 Methods

3.1 Spatio-temporal analysis

The monthly mobility pattern data in March in 2019, 2020 and 2021 were collected from SafeGraph and merged with core place dataset to get information about the POI's location and naics code. The merged data were aggravated to the tract level and mapped as polygon with geometry data from the U.S. Bureau. All Data processing steps were finished by Python 3.80.

In addition, spatial distribution of people's visits to public places in NYC was analyzed based on global and local Moran's I. Moran's I is a correlation coefficient to measures the similarity in neighboring places defined as Equation (1) (Moran, 1950). Large positive Moran's I (close to 1) indicates that strong positive auto-correlation and areas with similar values cluster together. Large negative values (close to -1) indicate strong negative auto-correlation and areas with dissimilar values cluster together.

$$\frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(X_i-\bar{X}\right)\left(X_j-\bar{X}\right)}{\sum_{i=1}^{n}\left(X_i-\bar{X}\right)^2} \tag{1}$$

In Equation (1), n is the number of observations. X_i is visit count at census tract i. X_j is the visit count at another location j. $\bar{X}$ is the mean value. w_{ij} is the spatial weights between tract i and tract j. If places i and j are neighbors, w_{ij} is close to 1; while they are not neighbors, w_{ij} equals zero. Neighbors are defined by queen criterion, which are places that share a common boundary or vertex. Global Moran's I was calculated to examine the existence of spatial clustering in visit count. Local Moran's I was calculated to evaluate the extent of spatial auto-correlation between place i and its vicinity. The significance assessment was calculated by pseudo p-value with 999 random permutation. All spatial auto-correlation analysis was calculated by using GeoDa 1.20.

The temporal changes of visit count between March 2019, March 2020 and March 2021 was calculated as Equation (2):

$$\text{change percentage } = \begin{cases} \frac{v_{t_1}-v_{t_0}}{v_{t_0}} \times 100\%, & v_{t_0} \neq 0 \\ \text{inf}, & v_{t_0} = 0 \end{cases} \tag{2}$$

In Equation (2), v_{i,t_1} is visit count of census tract i at t_1 time, and v_{i,t_0} is visit count of census tract i at t_0 time, and $t_1 \geq t_0$.

3.2 Correlation analysis

Associations between temporal changes of visit counts and contextual socio-economic factors at tract level were evaluated by correlation analysis. Before Pearson correlation coefficient were computed to indicate the relationships between predictors and dependent variables with significance levels of $p < 0.05$, two original-destination matrices were built based on the visitors' home tract id and POI's tract id. The first O-D matrix is inflow visit matrix, which records visit counts from all other places to a specific tract, while the outflow O-D matrix records visit counts from a specific home tract to all other places.

undecided: Thus, the dependent variables are the inflow visit density (inflow visit counts normalized by total population) and outflow visit density (outflow visit counts normalized by total population) in March 2020.

Wrangling from ACS 2019 5-year data, independent variables includes proportion of non-Hispanic white, proportion of non-Hispanic black, proportion of non-Hispanic Asian, proportion of Hispanic, proportion of population with at least bachelor's degree, proportion of vacant units, average household car ownership and average household median income.

3.3 Spatio-temporal analysis in income context

Combined with business type analysis, maps were created to show the human mobility in income context. Here, we not only compared the spatial characteristic of visit places in different income groups, but also analyzed the change degree of decreasing mobility in income context during the COVID-19 according to Equation 3.

$$\text{comparison of change degree between high-/low- income} = \begin{cases} \left(\frac{v^H_{i,t_1} - v^H_{i,t_0}}{v^H_{i,t_0}} - \frac{v^L_{i,t_1} - v^L_{i,t_0}}{v^L_{i,t_0}}\right) \times 100\%, & v_{t_0} \neq 0 \\ \text{inf}, & v_{t_0} = 0 \end{cases} \tag{3}$$

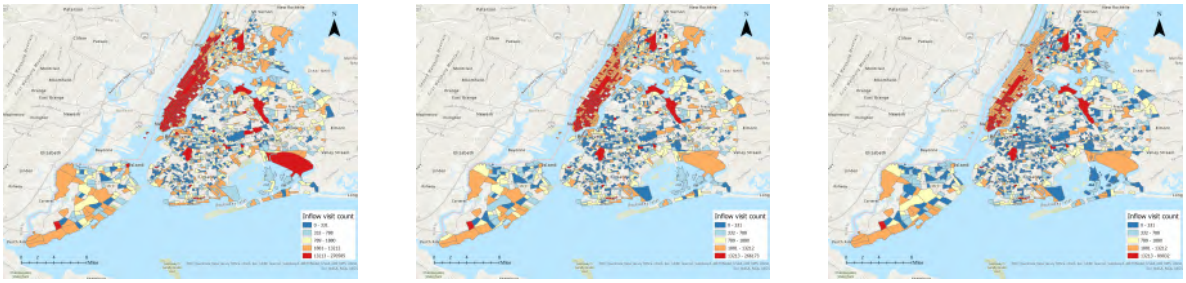
dd

In Equation (3), i is the destination tract id. v^H_{i,t_0} is visit count from the original tracts where the income are higher than the average income in NYC to destination i at t_0 time, and v^L_{i,t_0} is visit count from the original tracts where the income are lower than the average income in NYC to destination tract i at t_0 time, and $t_1 \geq t_0$.

4 Results

4.1 Spatio-termporal analysis

Choropleth maps for the total visits in NYC shows that Manhattan, John F. Kennedy (JFK) International Airport, LaGuardia Airport are the places people visit most often.

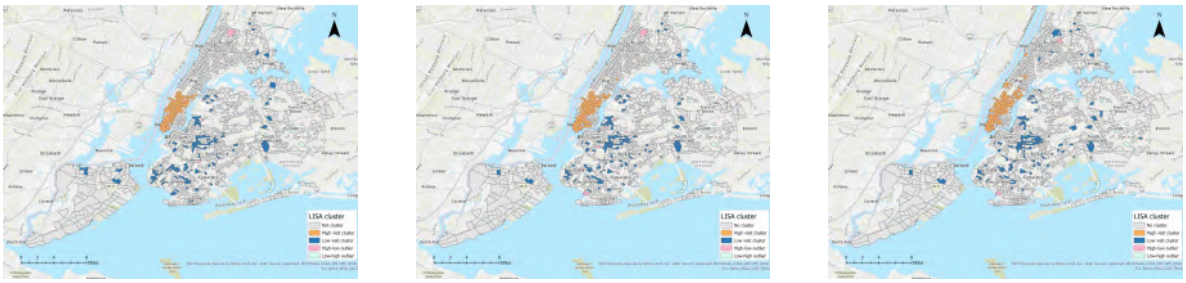


(a) March 2019 (b) March 2020 (c) March 2021

Figure 1: Visit count in different years

The global Moran's I values of visit count in 2019, 2020 and 2021 are 0.723, 0.566, and 0.378, indicating clustering pattern in human mobility. The result of local Moran's I is presented in Figure 2.

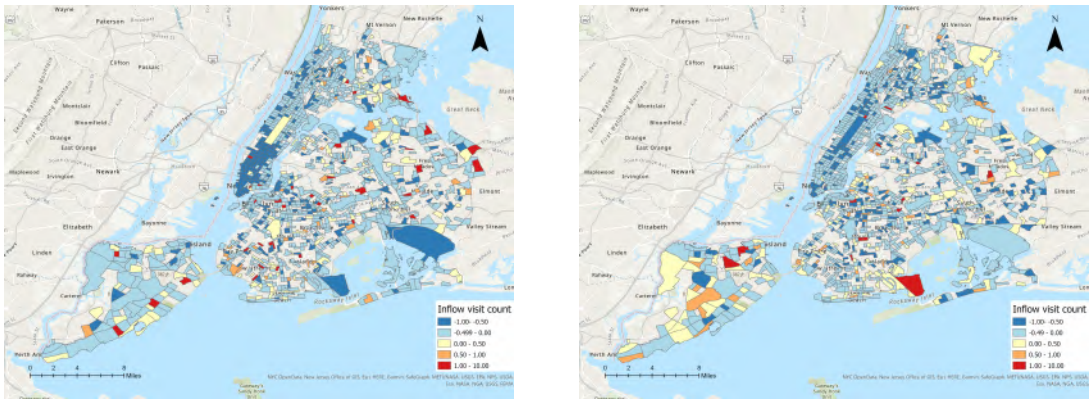
According to the map, clusters of high visited areas in 2019 were observed at Central Park, Midtown and Lower Manhattan, while clusters of low visited areas were spread in Brooklyn and Queens Boroughs. However, in 2021, northwestern area at the Bronx borough also became one of the high-visit-count spots.



(a) March 2019 (b) March 2020 (c) March 2021

Figure 2: Clustering map with local Moran's I statistics

Choropleth maps for the visit count change percentage in NYC shows that people continued to decrease their activities in the later two years. Particularly, people have decrease their visits to Lower Manhattan and JFK International Airport, LaGuardia Airport and Floyd Bennett Field in southeast Brooklyn Borough by 50%-100%. However, people did increase their visits to Central Park in Manhattan Borough during the COVID-19. In March 2021, visits to Staten Island and Woodlawn Heights in Bronx Borough. Woodlawn Heights is a predominantly Irish-American working class neighborhood at the north end Bronx Borough. Compared to March 2020, visits to Central Park, LaGuardia Airport and New York Library at Staten Island has decreased mostly, while visits to other places in Manhattan also had a 50%-0% drop.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 3: Percentage change of visit count

4.2 Business type analysis

Visits to public places has continually decreased from March 2019 to March 2021. Visits to professional and business services, accommodation, food wholesale and retail stores decreased more than 50% from March 2019 to March 2020. This significant decrease trend extends to March 2021 for transportation transit and accommodation places. Since education, transportation, food, wholesale and retail and health cares are necessary goods and services, the following sections describe the spatio-temporal changes of human mobility in these business categories in detail.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Accomodation	467745	196575	96993	-58%	-51%
Education	395591	221494	111892	-44%	-49%
Financial Activities	10235	6117	3658	-40%	-40%
Food	4887715	2122903	1214377	-57%	-43%
Goods Production	103881	52777	26788	-49%	-49%
Health Care	491347	321706	219743	-35%	-32%
Other	162728	95766	61500	-41%	-36%
Professional and Business Services	44009	17041	10561	-61%	-38%
Real Estate	139983	78127	53808	-44%	-31%
Recreation	4084598	3228826	2065839	-21%	-36%
Transportation	192828	95832	48065	-50%	-50%
Wholesale and Retail	2713860	1317471	795016	-51%	-40%

Table 2: Changes in different business categories

4.2.1 Education

As Mayor Bill de Blasio announced the 2-week all-remote learning in public schools from March 20 2020 in NYC, visits to education POI has decreased significantly.

Visits to schools decreased by 42% from 2019 to 2020 and 49% from 2020 to 2021. Particularly, visits to elementary and secondary schools which constitutes kindergarten through 12th grade show a 41% reduction from 2019 to 2020, and a 49% reduction from 2020 to 2021. In addition, visits to higher education dropped by 49% in March 2020. Technical schools include junior colleges, automobile driving schools, cosmetology and barber schools and other technical and trade schools. Visits to technical schools saw a 58% decrease from 2019 to 2021.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Colleges, Universities, and Professional Schools	23102	11702	5985	-49%	-49%
Elementary and Secondary Schools	291072	171292	87885	-41%	-49%
Technical School	7620	3160	1312	-59%	-58%
Total visit count	340251	196646	100045	-42%	-49%

Table 3: Percentage change in education subcategories

4.2.2 Transportation

Visits to transportation system has decreased by 50% from 2019 to 2020 and from 2020 to 2021. Particularly, visits to airport has decreased by 53% from 2019 to 2020 and decreased by 52% from 2020 to 2021. Visits to bus and other motor vehicle transit system had a noticeable 68% decrease in 2020 and a smaller 12% reduction in 2021. Visits to line-hail railroads was decreased by 40% in the first year of COVID-19, and remained 40% decreasing rate from 2020 to 2021. However, contrasting to the general decreasing trend, water vehicle transportation saw a increase from 2019 to 2020. For example,

the visits to port and harbor operations increased 10 times from 2019 to 2020. However, from 2020 to 2021, the count decreased to value in 2019. In addition, from 2019 to 2020, visits to inland water passenger transportation increased by 12%. However, from 2020 to 2021, it decreased by 45%.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Airport	178839	84109	40778	-53%	-52%
Line-Haul Railroads	3821	2281	1398	-40%	-39%
Bus and Other Motor Vehicle Transit Systems	4136	1318	1166	-68%	-12%
Port and Harbor Operations	187	2073	186	1009%	-91%
Inland Water Passenger Transportation	883	992	549	12%	-45%
Total visit count	192334	95329	47437	-50%	-50%

Table 4: Percentage change in transportation subcategories

4.2.3 Food

Visits to places in food has decreased by 57% from 2019 to 2020 and with smaller drop from 2020 to 2021: about 44%. Particularly, visits to drinking places, full-service restaurants and limited-service restaurants(e.g. fast-food restaurants and takeout eating places) all show a 59% decrease from 2019 to 2020.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Caterers	52018	23190	13177	-55%	-43%
Drinking Places (Alcoholic Beverages)	547215	223974	131639	-59%	-41%
Full-Service Restaurants	1989470	816758	491380	-59%	-40%
Limited-Service Restaurants	1031002	419592	227798	-59%	-46%
Snack and Nonalcoholic Beverage Bars	926039	462201	235293	-50%	-49%
Total visit count	4545744	1945715	1099287	-57%	44%

Table 5: Percentage change in food subcategories

4.2.4 Wholesale and Retail

Visits to places in wholesale and retail has decreased by 34% from 2019 to 2020, and decreased by 41% from 2020 to 2021 in total. Particularly, from 2019 to 2020, visits to supermarkets and grocery retailers(except convenience retailers) had decreased by 33%. Visits to fruit and vegetable retailers, and drug merchant wholesale decreased by more than 40% in 2020. In 2021, the mobility pattern finds a 43% decrease in visits to supermarket and grocery, and a 35% reduction in visits to fruit and vegetable stores decreased by 35% in 2021. However, visits to drug merchant wholesale shows a trivial 2% increase from 2020 to 2021.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Drugs and Druggists' Sundries Merchant Wholesalers	1193	618	628	-48%	2%
Fruit and Vegetable Retailers	14857	8315	5379	-44%	-35%
Supermarkets and Other Grocery Retailers (except Convenience Retailers)	114498	77034	43662	-33%	-43%
Total visit count	167629	110027	64228	-34%	-42%

Table 6: Percentage change in wholesale and retail subcategories

4.2.5 Health Care

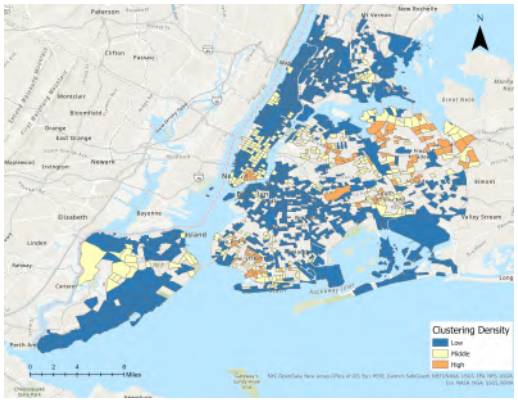
Visits to places in health care has decreased by 35% from 2019 to 2020, and decreased by 32% from 2020 to 2021. Especially, from 2019 to 2020, visits to nursing care centers(e.g. convalescent hospitals) and Physicians' office have decreased by more than 40%. Visits to child care hospital and services has decreased by 35%. However, in 2021, the visit count to child care services dropped by 48% compared to 2020. And the visit to nursing care facilities also dropped by 44%.

Sub-category	2019 visit	2020 visit	2021 visit	2019-2020 change percent	2020-2021 change percent
Child Care Services	89217	58072	30109	-35%	-48%
General Medical and Surgical Hospitals	148910	105307	83648	-29%	-21%
Kidney Dialysis Centers	40091	28468	18973	-29%	-33%
Offices of Physicians (except Mental Health Specialists)	82857	49998	35717	-40%	-29%
Nursing Care Facilities (Skilled Nursing Facilities)	5338	2983	1660	-44%	-44%
Total visit count	471345	307228	210259	-35%	-32%

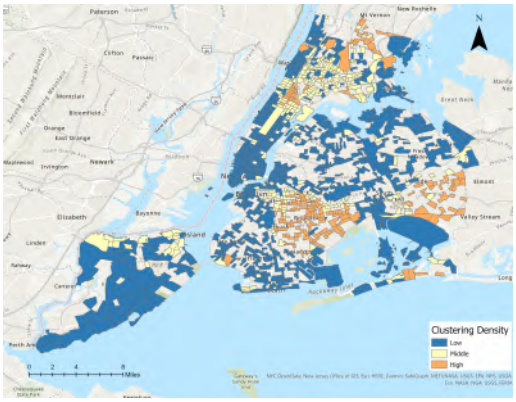
Table 7: Percentage change in health care subcategories

4.3 Correlation Analysis

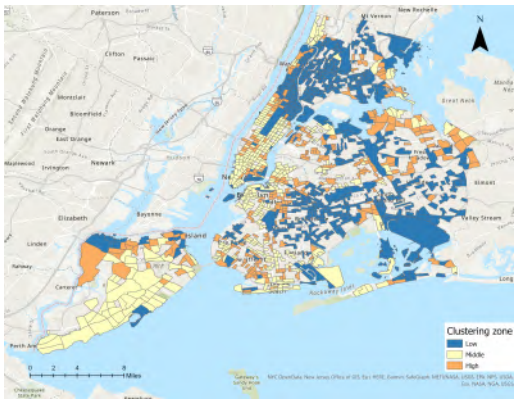
Correlation coefficients were computed to indicate the relationships between the temporal change of visit counts in March 2019 and March 2020 and socio-economic variables such as median household income, race composition, vacancy rate, education attainment, poverty rate and car ownership .



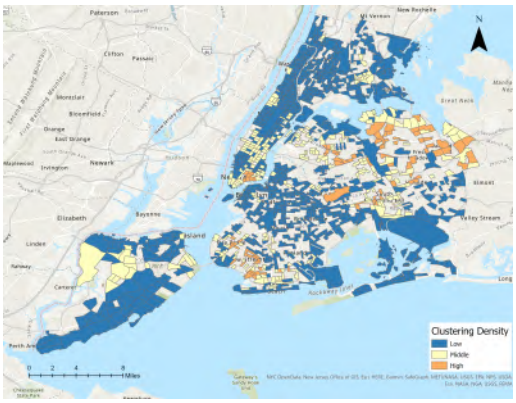
(a) Asian percent



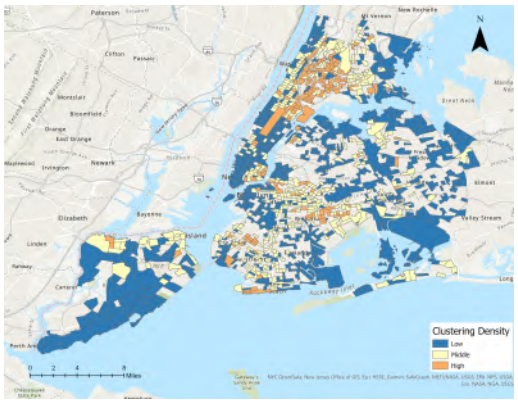
(b) Black percent



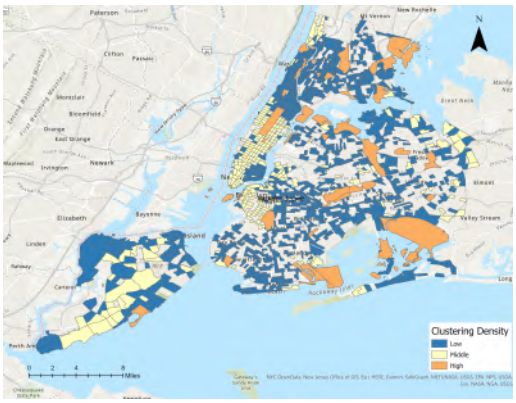
(c) White percent



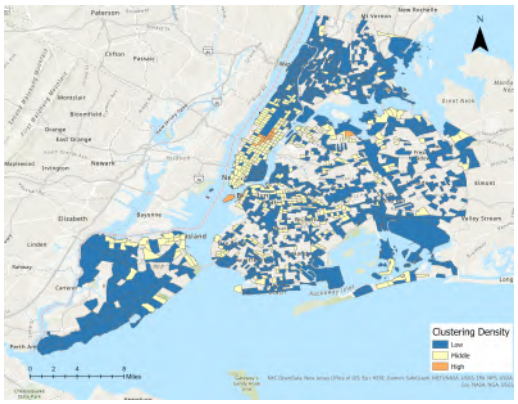
(d) Hispanic percent



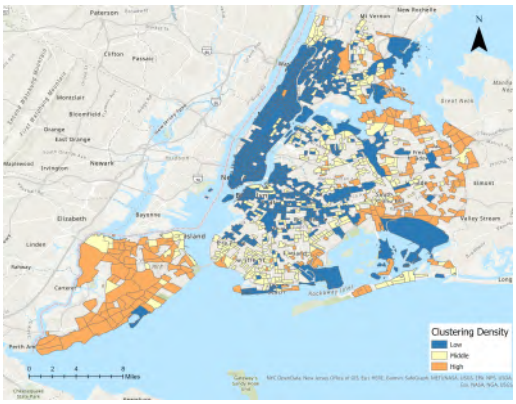
(e) Poverty rate



(f) Household income



(g) Vacant rate



(h) Car ownership

Figure 4: K-means clustering of socio-economic factors

With significance levels of $P < 0.05$, the proportion of White, and average number of car in household have positive correlation with change of outflow visit count between March 2019 and March 2020. Proportion of vacant units, proportion of people with at least bachelor's degree, and median household income have negative correlation with outflow visit count change. This indicates areas with low proportion of white race, low proportion of car ownership, high vacant rate, high education attainment and high median household income tend to large decrease in visiting other places in NYC during COVID-19.

As for the correlation analysis between **inflow** visit count change and socio-economic factors, the household average number of car was found have sttrong positive correlation with visit counts. Proportion of vacant units, proportion of people with at least bachelor's degree, median household income and poverty rate tend to have negative correlation with visit count change. This indicates people tend to decrease their visits to areas with high vacancy rate, high poverty rate and high education attainment, high median household income and low car ownership rate during the pandemic.

Variables	Inflow visit count		Outflow visit count change	
	coefficient	P value	correlation	P value
Constant	-729.7	**0.00011**	14086	**0.00000**
Proportion of White	550.337	**0.00598**	2543.8	0.28115
Proportion of Black	532.396	**0.01376**	-654.387	0.78485
Proportion of Indian	-3361.88	0.43181	-1583.32	0.98036
Proportion of Asian	511.006	0.08222	-1583.32	0.98036
Household Car Ownership	93.6421	0.32771	6385.25	**0.00000**
Vacancy Rate	-65.1777	0.90043	-64113	**0.00000**
Poverty Rate	1624.65	**0.00001**	-21036	**0.00007**
Percent of Bachelor Degree	1338.72	0.58559	-150572	**0.00000**
Median Household Income	-2.51236e-6	**0.00000**	-7629.32	**0.01476**

Table 8: Correlationship for predictors and visit count change between March 2019 and March 2020. Bold values are significant at $P < 0.05$.

4.4 Spatio-temporal analysis in income contexts

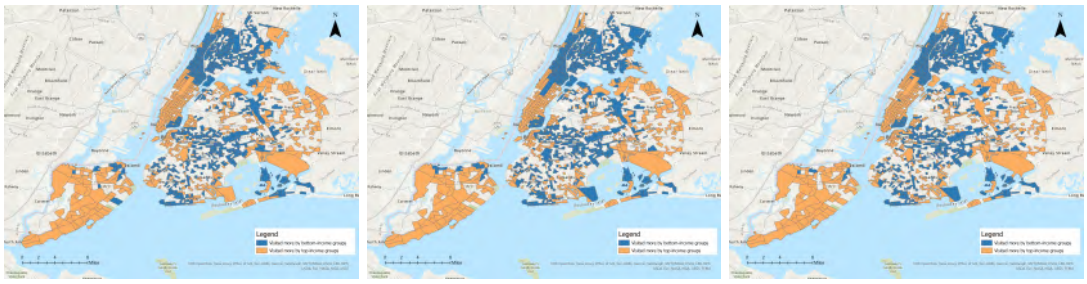
The temporal changes of human mobility in different contexts at tract level was assessed to analyze COVID-19's impact on social equity by spatial and correlation analysis.

4.4.1 Total visits

Human mobility pattern in NYC was analyzed in income contexts. Top-income groups represent people living in the tracts where the local income is at the top quartile level in NYC. Bottom-income groups represent people living in the tracts where the local income is at the bottom quartile level in NYC.

First, the comparison of visit count in bottom- and top- income groups were analyzed in Figure (5). The blue areas are places where were more often visited by low-income residents. The yellow areas represent places where were visited more by high-income residents. Combined with clustering pattern of socio-economic factors, high-income groups were observed to have more visit to Lower Manhattan, Staten Island and outskirt of Queen Borough, where are places with high proportion of white race, high household income. Particularly, Lower Manhattan and north Staten Island have high vacancy rate, and Staten Island as well as outskirt of Queen Borough have high car ownership. Low-income groups tend to have more visits to Upper Manhattan, Bronx Borough, Brooklyn Borough and south

Queen Borough. There are places with high clustering of racial minority, and relative high poverty rate, and low household income.

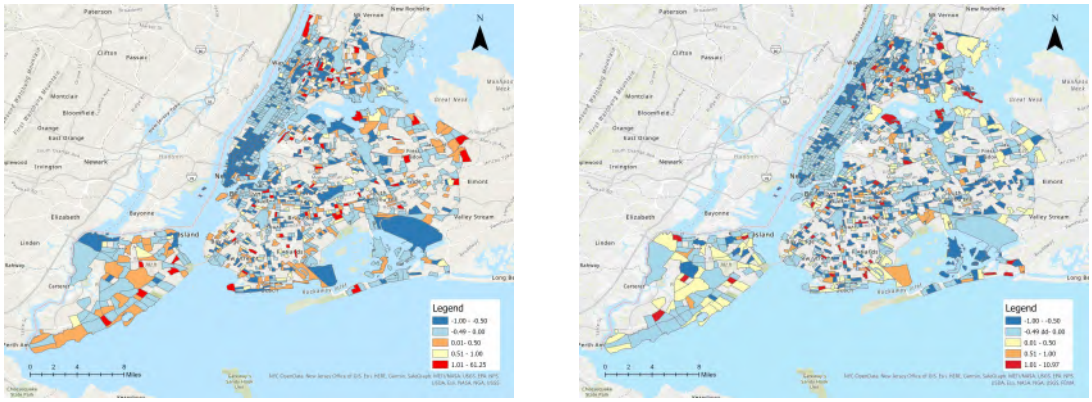


(a) March 2019 (b) March 2020 (c) March 2021

Figure 5: Comparison of visit count between top-income group and bottom-income group

Second, the change percent of visit count in top-income groups were analyzed according to Equation (2). A general decrease trend in visit count in all income groups was observed from 2020 to 2021.

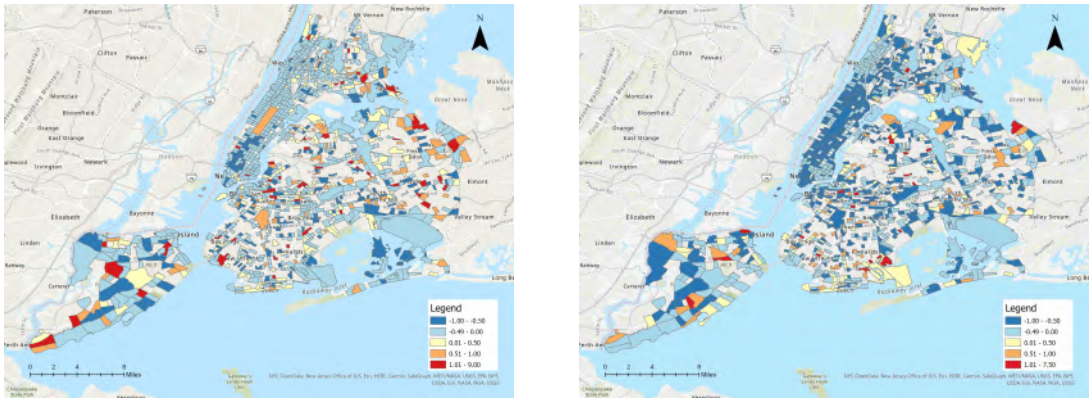
In March 2020, top-income groups visited Lower Manhattan, JFK International Airport and La-Guardia Airport at Queens Borough with a over 50% decrease. At the same time, their visits had 0-50% decrease to Upper Manhattan, and west shore, northern and eastern areas in Staten Island Borough. However, there was an increase in visit count to Staten Island and outskirt of southeast shore of Brooklyn and north end of Queens Borough in March 2020. In March 2021, top-income groups had a 0-50% decrease in visit counts to Central Manhattan, west shore, northern and eastern areas in Staten Island Borough. However, increases were observed in Staten Island and northeastern Bronx Borough. A significant 50%-100% increase in visit counts was found in Floyd Bennett Field in southeast Brooklyn Borough. In addition, top-income people's visits to central Staten Island and northeastern Bronx Borough increased by 0-50%.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 6: Percentage change of visit count of people from top quartile income tract

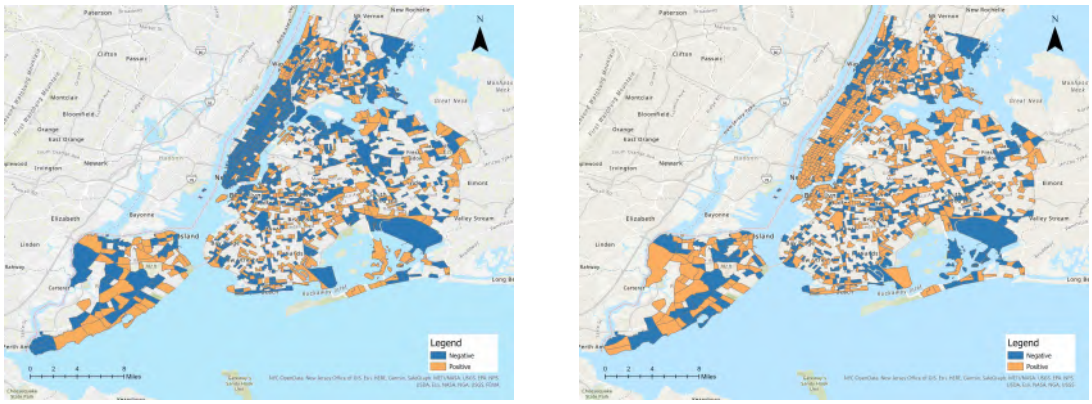
As for bottom-income groups, their visits to Manhattan, JFK, and Pleasant Plains neighborhood in south Staten Island Borough dropped by 50%-100% in 2020. Visits from this group to Lower Manhattan decreased by over 50%. However, visits to Central Park increased by 95.3%. In addition, visits to two neighborhoods in south and east shore in Staten Island Borough increased by 100%. In 2021, the decreasing rate of visits from bottom-income tracts in Manhattan was larger than 50%. For example, people's visits to Central Park has decreased by 84.5% compared to last year.



(a) From 2019 to 2020 (b) From 2020 to 2021

Figure 7: Percentage change of visit count of people from bottom quartile income tract

Third, the change degree of visit count in different years in bottom- and top- income groups were analyzed according to Equation (3) and showed in Figure (8). The blue color means the difference of visit change percentage between top- and bottom- income group difference is negative, and the yellow color represents the difference is positive. From 2019 to 2020, the difference of visit count change percentage between top- and bottom- income groups in most areas in Manhattan, JFK and Staten Island are negative, indicating bottom-income groups decreased their visits to these areas in smaller degree during the outbreak of COVID-19. From 2020 to 2021, the difference of visit count percentage between top-income to bottom-income groups change are positive in most areas, indicating bottom-income groups decreased their visits to most places in New York in larger degree.

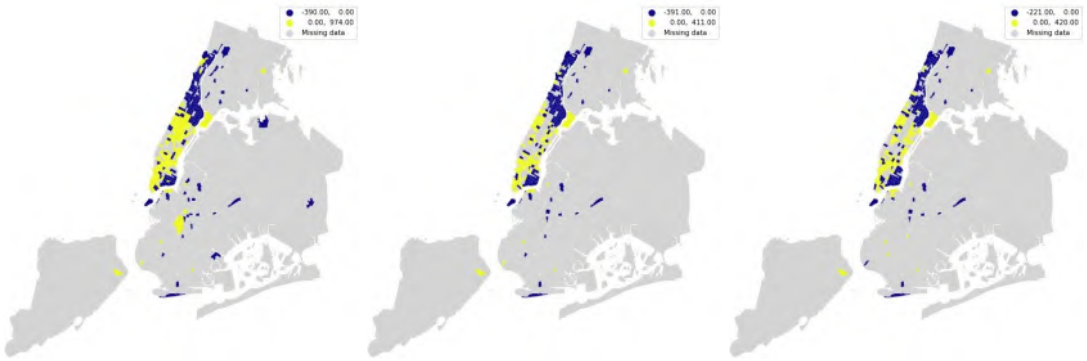


(a) From 2019 to 2020 (b) from 2020 to 2021

Figure 8: Comparison of the percentage change between top-income group and bottom-income group

4.4.2 Visit counts to education POIs in income context

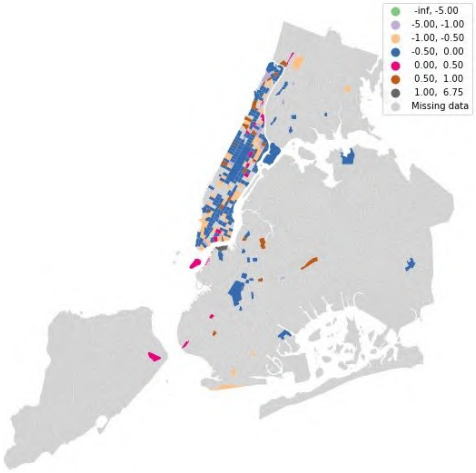
Top-income groups tend have more visits to educational places in high-income areas such as Lower and Central Manhattan, while bottom-income groups had larger volume visits to schools at high-poverty rate areas such as Upper Manhattan and Lower East side at south Manhattan.



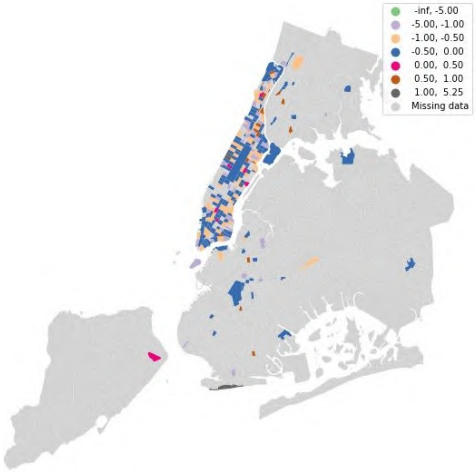
(a) March 2019 (b) March 2020 (c) March 2021

Figure 9: Comparison of visit count to education POIs between top-income group and bottom-income group

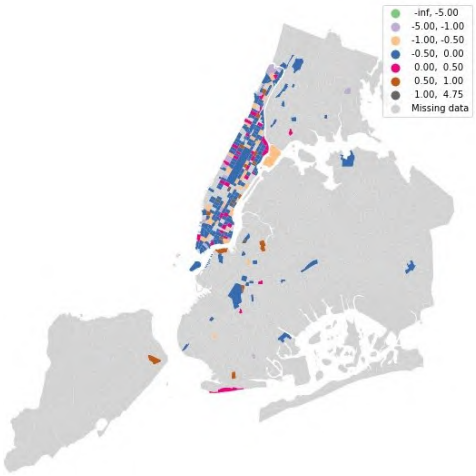
In March 2020 and March 2021, top-income groups decreased their visits to all educational places in New York. However, bottom-income groups were observed with 0-50% increase to some educational places in Manhattan during the first month of COVID-19.



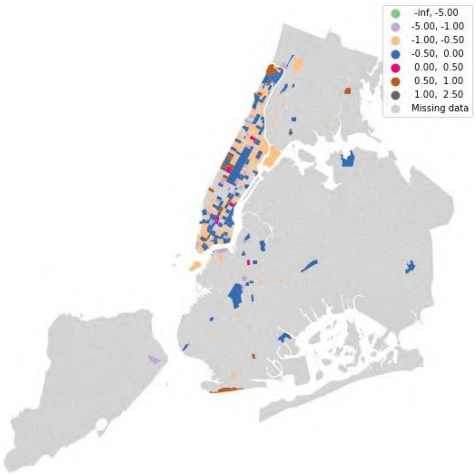
(a) Change in top-income groups from March 2019 to March 2020



(b) Change in top-income groups from March 2020 to March 2021



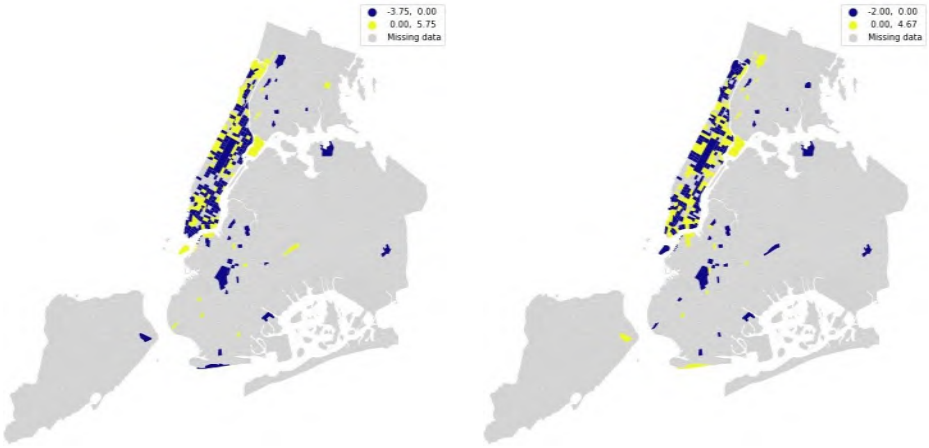
(c) Change in bottom-income groups from March 2019 to March 2020



(d) Change in bottom-income groups from March 2020 to March 2021

Figure 10: Percentage change of visit counts to education places in income context

In March 2020, bottom-income groups tend to have smaller degree of visit count decrease to educational POIs in Lower and Central Manhattan, while they have larger degree of decrease to schools in Upper Manhattan. In March 2021, bottom-income groups had larger degree of visit count decrease to most schools in Manhattan.



(a) From 2019 to 2020 (b) from 2020 to 2021

Figure 11: Comparison of the percentage change to education POIs between top-income group and bottom-income group

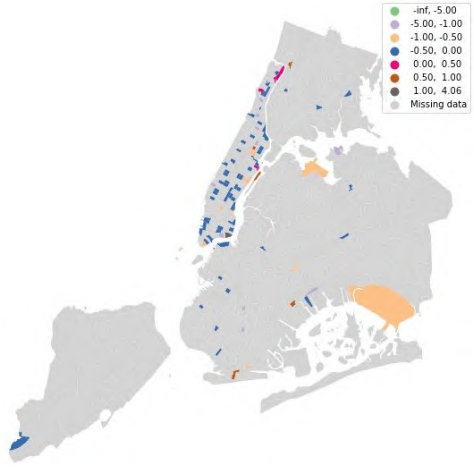
4.4.3 Visit counts to transporation POIs in income context

High-income groups were observed to have more visit to JFK International Airport, LaGuardia Airport, and Tottenville neighborhood on the south shore of Staten Island in the March 2019 and March 20. However, low-income people had higher visit counts to JFK in March 2021.

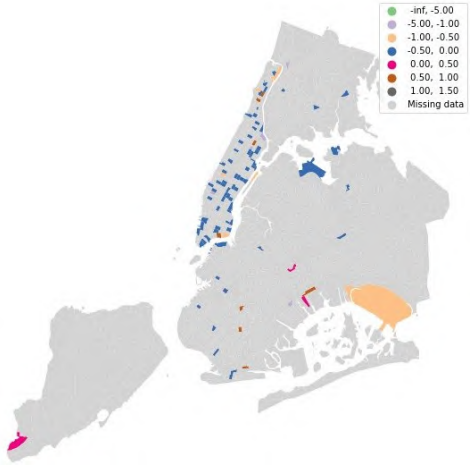
(a) March 2019 (b) March 2020 (c) March 2021

Figure 12: Comparison of visit count to transporataion POIs between top-income group and bottom-income group

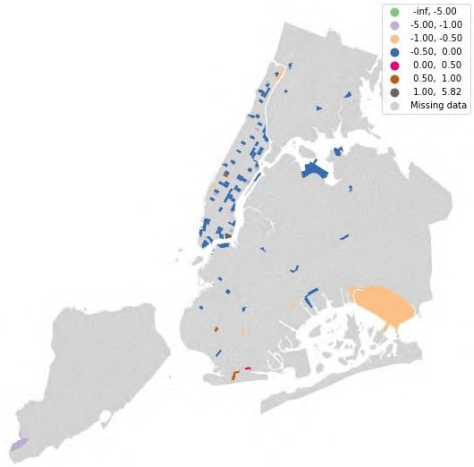
In March 2020 and March 2021, top-income groups decreased their visits to all transportation places in New York. Bottom-income groups decreased their visits to all transportation POIs compared to the same time last year.



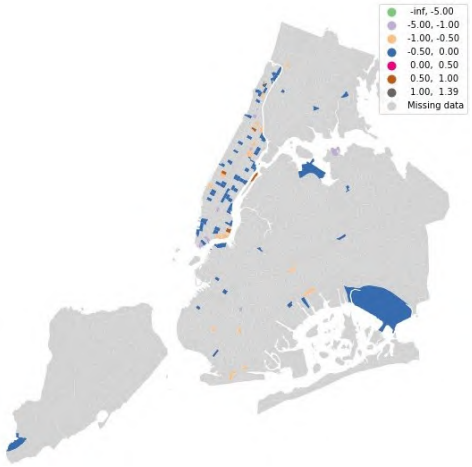
(a) Change in top-income groups from March 2019 to March 2020



(b) Change in top-income groups from March 2020 to March 2021



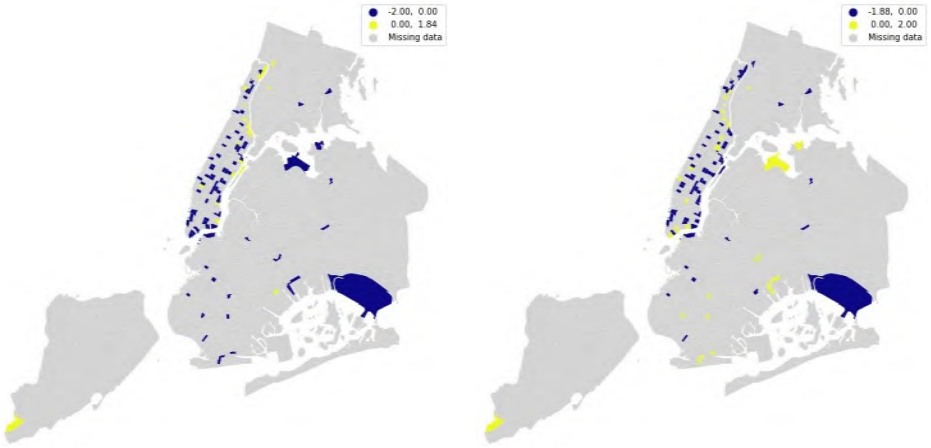
(c) Change in bottom-income groups from March 2019 to March 2020



(d) Change in bottom-income groups from March 2020 to March 2021

Figure 13: Percentage change of visit counts to transportation POIs in income context

Compared to the same time in 2019, bottom-income groups had smaller degree of visit count decrease to transportation POIs in March 2020. However, bottom-income groups had larger degree of visit count decrease to LaGuardia airport in March 2021,.

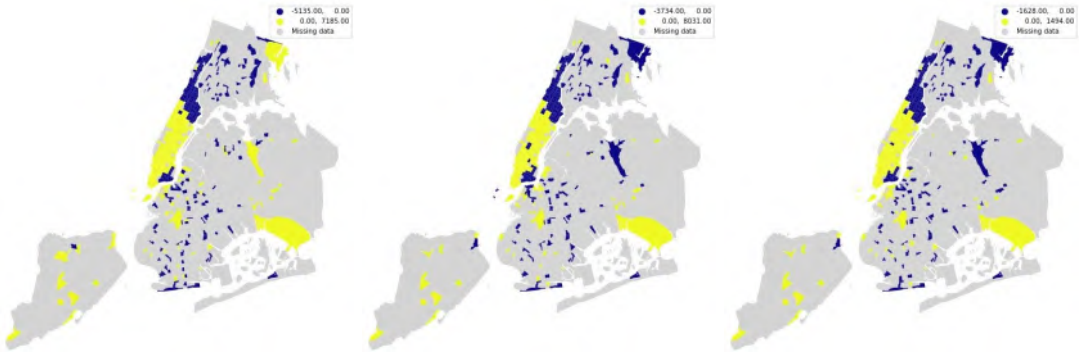


(a) From 2019 to 2020 (b) from 2020 to 2021

Figure 14: Comparison of the percentage change to transportation POIs between top-income group and bottom-income group

4.4.4 Visit counts to food POIs in income context

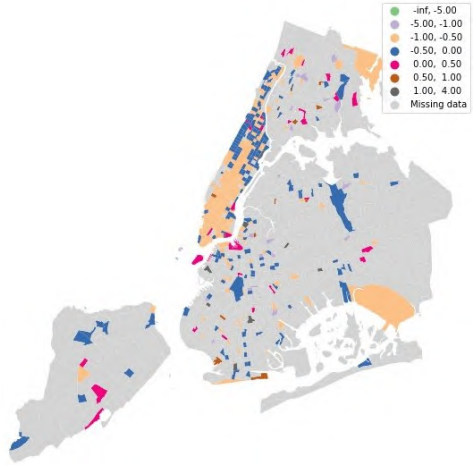
As showed in Figure 24, top-income groups tended to have more visits to restaurants in Lower and Central Manhattan, Staten Island and JFK airport all the time. While bottom-income groups tend to have more visits to food POI at Upper Manhattan, Bronx Borough, and Brooklyn Borough. In March 2019, bottom-income people visited more time to Throggs Neck Neighborhood at south-eastern Bronx Borough and Flushing Meadows Corona Park at northern Queen Borough. However, in the March of 2020 and 2021, top-income people tend to have more visits counts to these places than bottom-income residents.



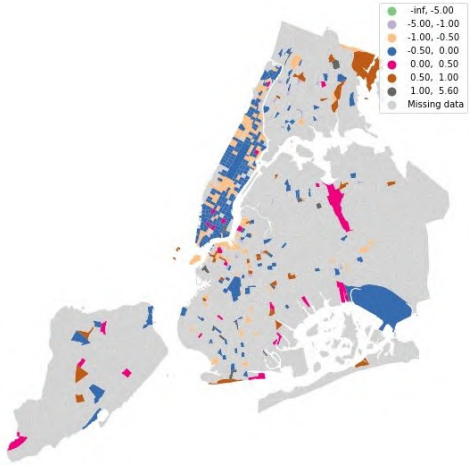
(a) March 2019 (b) March 2020 (c) March 2021

Figure 15: Comparison of visit count to food POIs between top-income group and bottom-income group

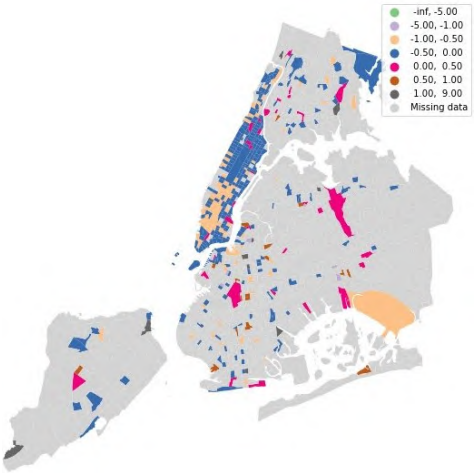
In March 2020, top-income groups decreased their visits to most restaurants places in New York. In March 2021, there was an increase in visits to Flushing Meadows Corona Park from top-income people. As for the bottom-income groups, there were a significant increase to restaurants at JFK in March 2021.



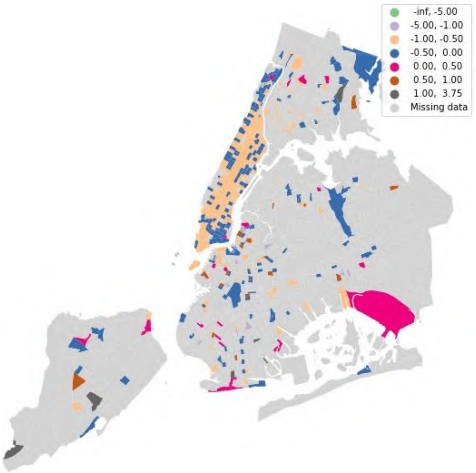
(a) Change in top-income groups from March 2019 to March 2020



(b) Change in top-income groups from March 2020 to March 2021



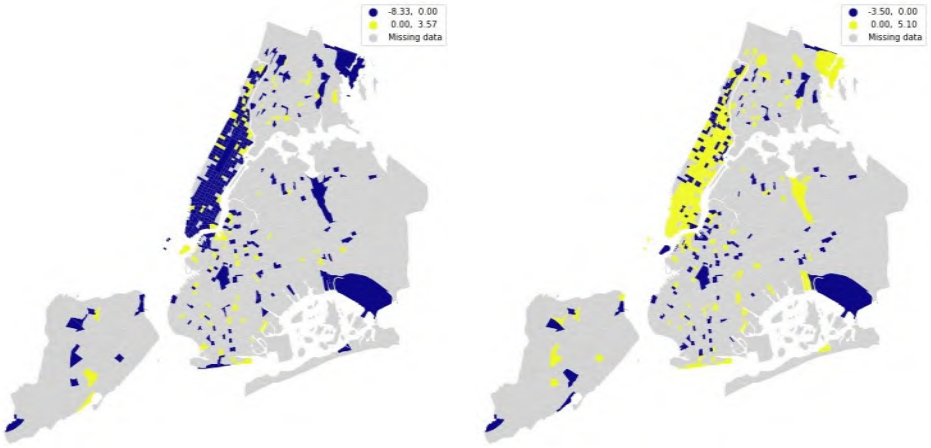
(c) Change in bottom-income groups from March 2019 to March 2020



(d) Change in bottom-income groups from March 2020 to March 2021

Figure 16: Percentage change of visit count to food POIs in income context

During the outbreak of COVID-19, top-income groups had larger degree of visit decrease to most food POIs in NYC, while they had smaller degree of decrease to restaurants in Manhattan after COVID-19.

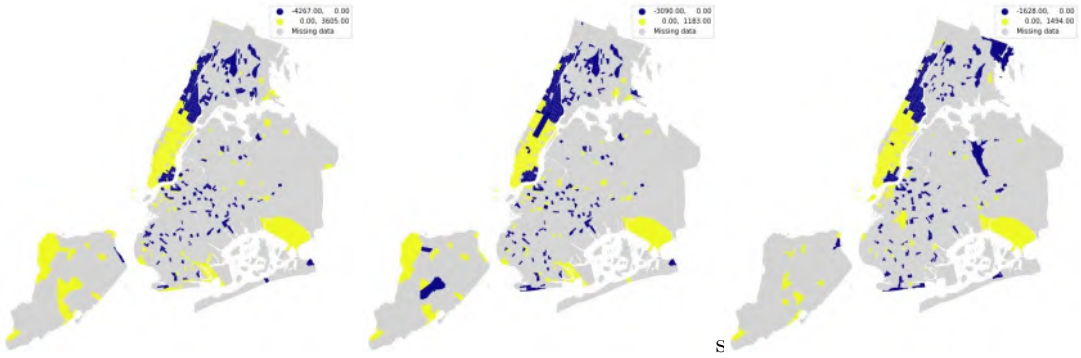


(a) From 2019 to 2020 (b) from 2020 to 2021

Figure 17: Comparison of the percentage change to food POIs between top-income group and bottom-income group

4.4.5 Visit counts to wholesale and retail POIs in income context

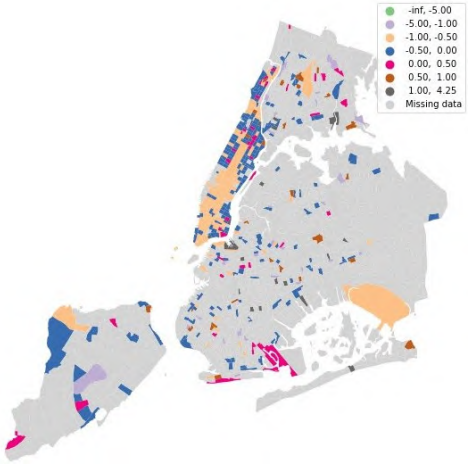
As showed in Figure 18, top-income groups tend to have more visits to wholesale markets and retail stores in Lower and Central Manhattan, Staten Island and JFK airport all the time. While bottom-income groups tend to have more visits to food POI at Upper Manhattan, Bronx Borough, and Brooklyn Borough.



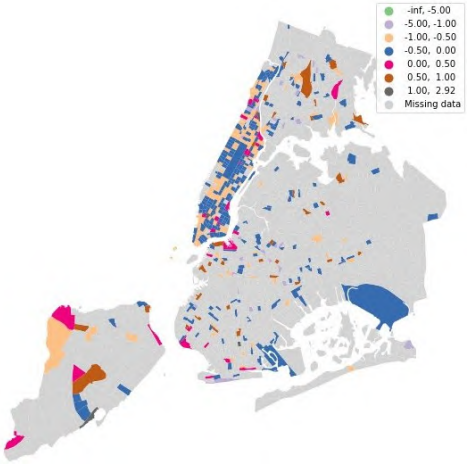
(a) March 2019 (b) March 2020 (c) March 2021

Figure 18: Comparison of visit count to wholesale and retail POIs between top-income group and bottom-income group

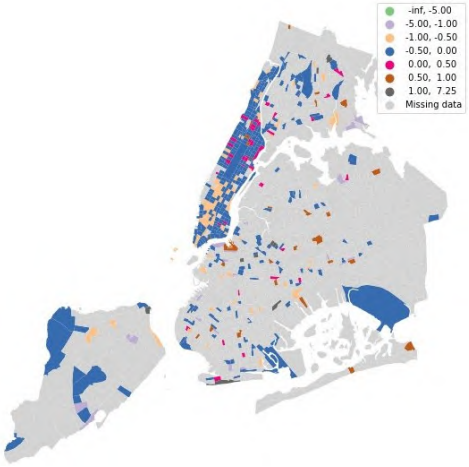
In March 2020 and March 2021, top-income groups continued to decrease their visits to most wholesale and retail POIs. The same trend was observed in the bottom-income groups.



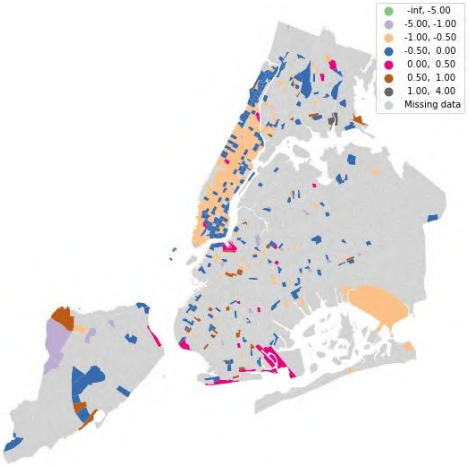
(a) Change in top-income groups from March 2019 to March 2020



(b) Change in top-income groups from March 2020 to March 2021



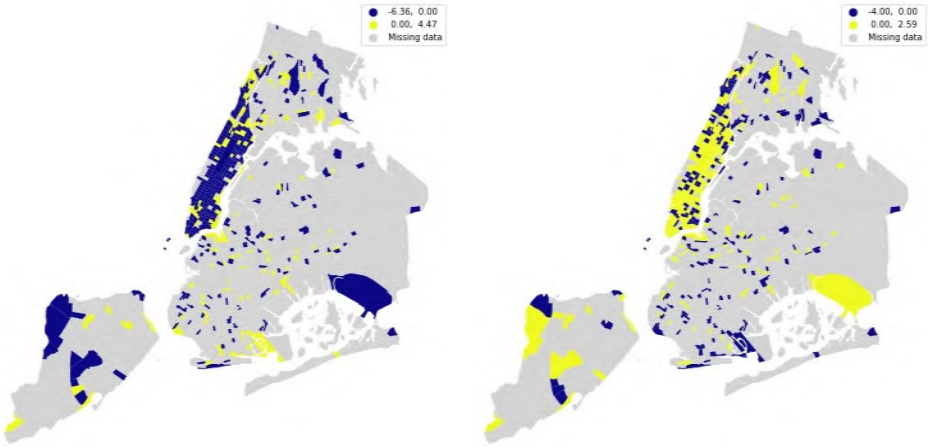
(c) Change in bottom-income groups from March 2019 to March 2020



(d) Change in bottom-income groups from March 2020 to March 2021

Figure 19: Percentage change of visit count to wholesale and retail POIs in income context

During the outbreak of COVID-19, top-income groups had larger degree of visit decrease to most wholesale and retails POIs in NYC except Marine Park neighborhood in southeastern Brooklyn, while bottom-income groups had larger degree of decrease to wholesale and retail stores in Manhattan and Staten Island after COVID-19.

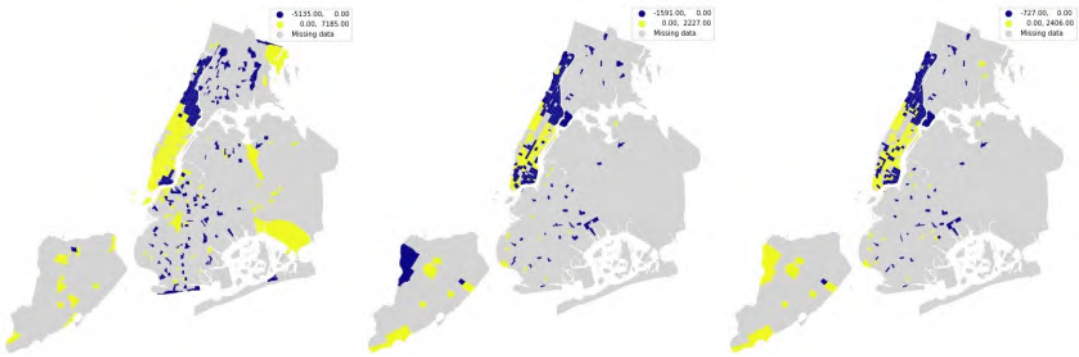


(a) From 2019 to 2020 (b) from 2020 to 2021

Figure 20: Comparison of the percentage change to wholesale and retail POIs top-income group and bottom-income group

4.4.6 Visit counts to health care POIs in income context

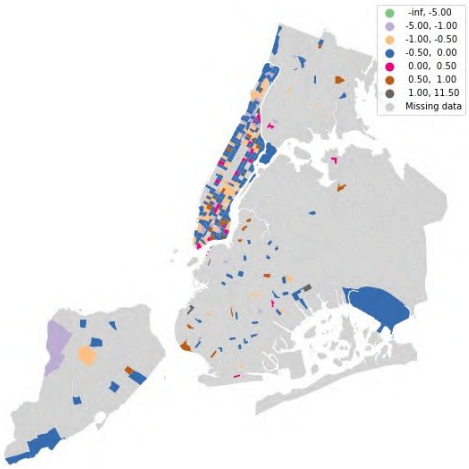
As showed in Figure 24, top-income groups tended to have more visits to health care POIs in Lower and Central Manhattan, Staten Island and JFK airport all the time. While bottom-income groups tend to have more visits to health care POI at Upper Manhattan, Lower East Side at Lower Manhanttan, and Brooklyn Borough.



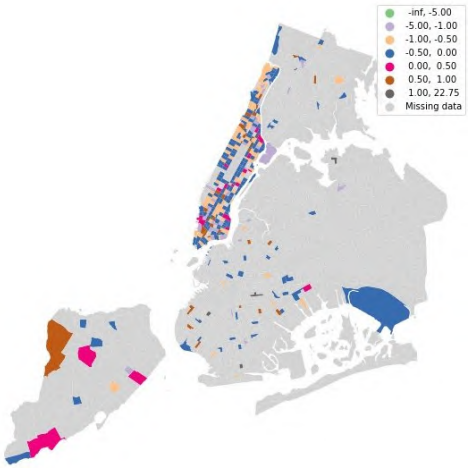
(a) March 2019 (b) March 2020 (c) March 2021

Figure 21: Comparison of visit count to health care POIs between top-income group and bottom-income group

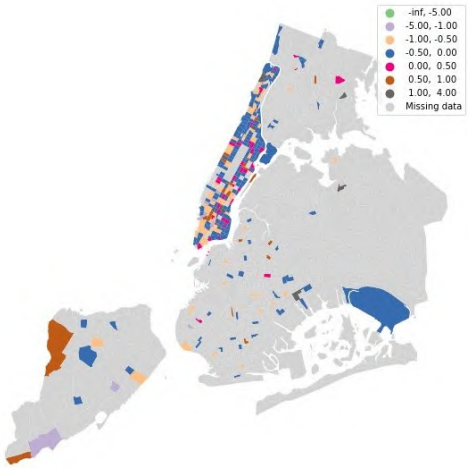
In March 2020 and March 2021, top-income groups decreased their visits to most health care places in New York. In March 2021, there was an increase in visits to Flushing Meadows Corona Park from top-income people, there was no significant increase. However, there were significant increase to health care places at Manhattan in March 2021 in bottom-low income groups.



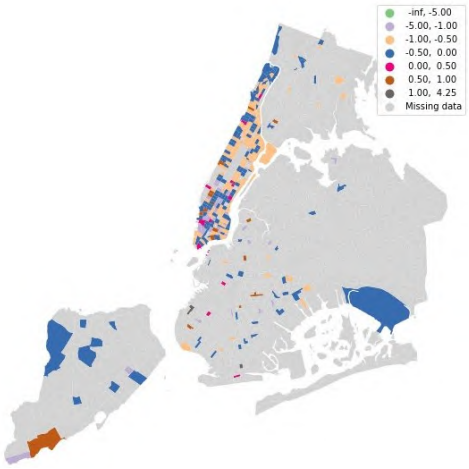
(a) Change in top-income groups from March 2019 to March 2020



(b) Change in top-income groups from March 2020 to March 2021



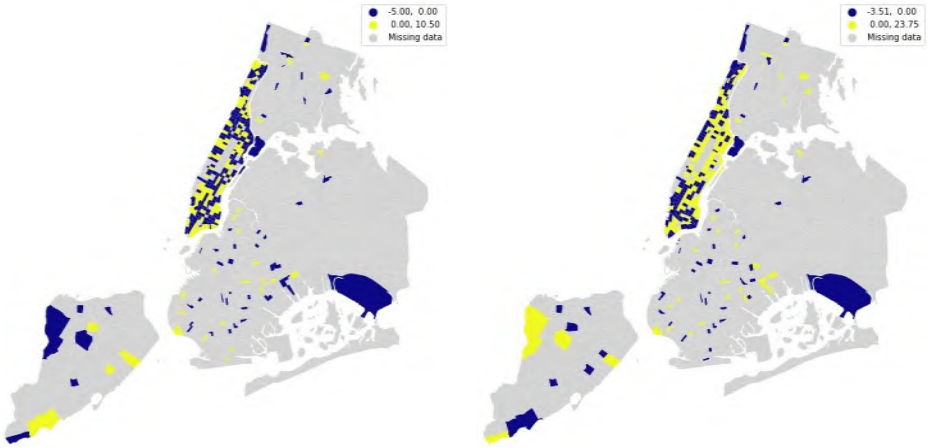
(c) Change in bottom-income groups from March 2019 to March 2020



(d) Change in bottom-income groups from March 2020 to March 2021

Figure 22: Percentage change of visit count to health care POIs in income context

During the outbreak of COVID-19, top-income groups had larger degree of visit decrease to health care POIs in Financial District in Downtown areas, Murray Hill, East Midtown in Midtown areas, Central Park, El Bario at Uptown areas, Harlem Upper areas at Manhattan, and most places at Brooklyn Borough. At the same time, bottom-income groups have larger degree to Chinatown and Soho in Downtown areas, Murray Hill, East Midtown in Midtown areas, Upper Side near Central Park, and Harlem areas at Manhattan.

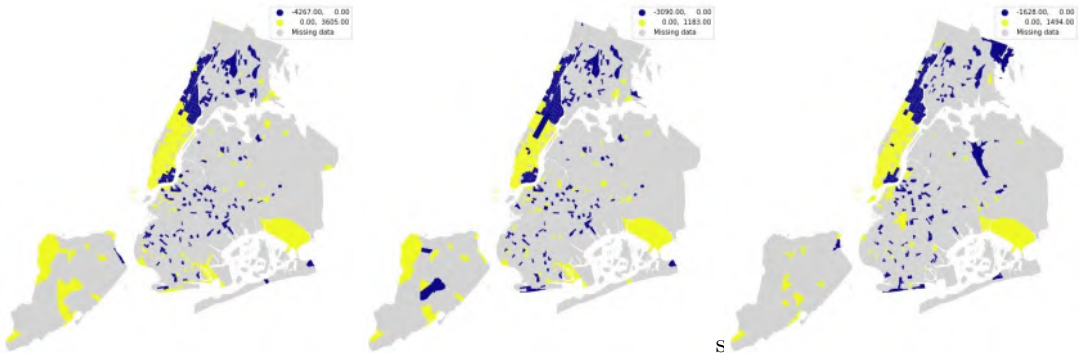


(a) From 2019 to 2020 (b) from 2020 to 2021

Figure 23: Comparison of the percentage change to health care POIs between top-income group and bottom-income group

4.4.7 Visit counts to wholesale and retail POIs in income context

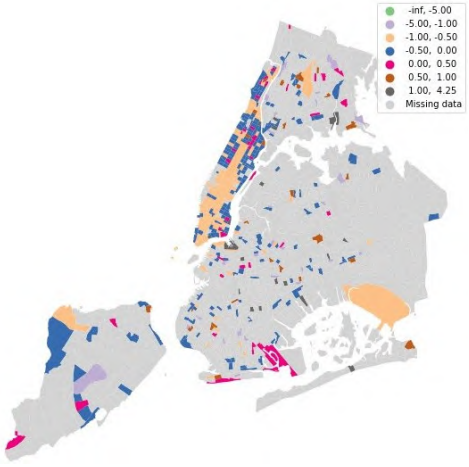
As showed in Figure 18, top-income groups tend to have more visits to wholesale markets and retail stores in Lower and Central Manhattan, Staten Island and JFK airport all the time. While bottom-income groups tend to have more visits to food POI at Upper Manhattan, Bronx Borough, and Brooklyn Borough.



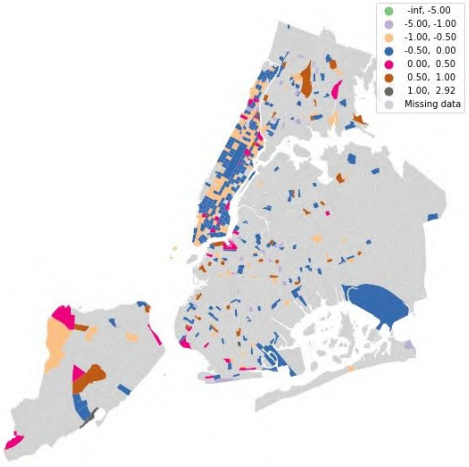
(a) March 2019 (b) March 2020 (c) March 2021

Figure 24: Comparison of visit count to food POIs between top-income group and bottom-income

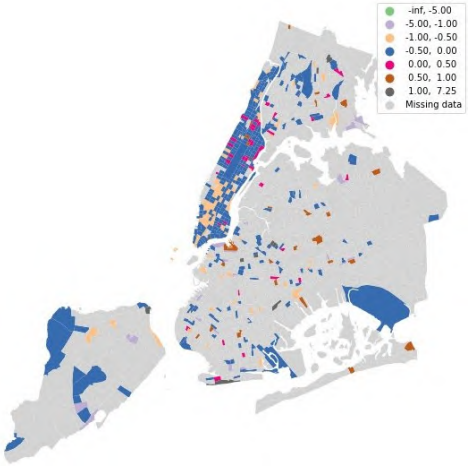
In March 2020 and March 2021, top-income groups continued to decrease their visits to most wholesale and retail POIs. The same trend was observed in the bottom-income groups.



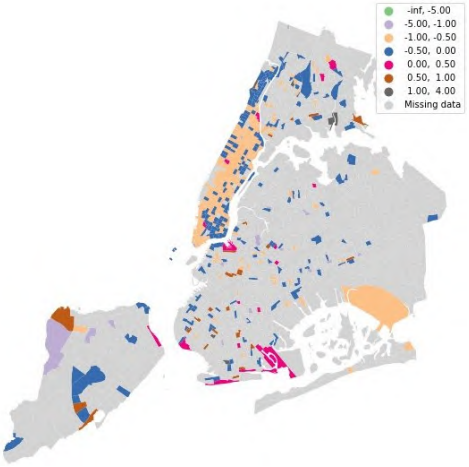
(a) Change in top-income groups from March 2019 to March 2020



(b) Change in top-income groups from March 2020 to March 2021



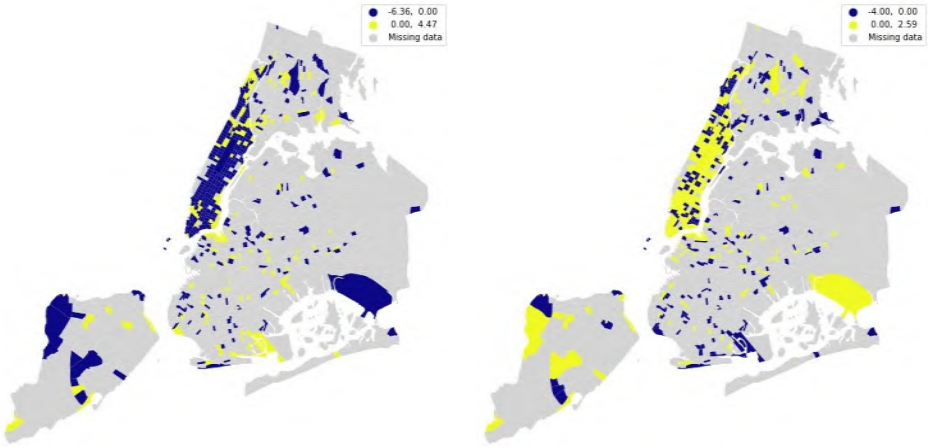
(c) Change in bottom-income groups from March 2019 to March 2020



(d) Change in bottom-income groups from March 2020 to March 2021

Figure 25: Percentage change of visit count to wholesale and retail POIs in income context

During the outbreak of COVID-19, top-income groups had larger degree of visit decrease to most wholesale and retails POIs in NYC except Marine Park neighborhood in southeastern Brooklyn, while bottom-income groups had larger degree of decrease to wholesale and retail stores in Manhattan and Staten Island after COVID-19.



(a) From 2019 to 2020 (b) from 2020 to 2021

Figure 26: Comparison of the percentage change to wholesale and retail POIs between top-income group and bottom-income group

5 Discussion

This study characterizes the spatial distribution and temporal shifting of human mobility before, during and after COVID-19, as well as compares the change rate in socio-economic contexts to analyze social equity issues.

First, this study captures the general reduction trend in human mobility during the pandemic and this decreasing trend was maintained through to the March of 2021(Figure 1). Particularly, visits to necessary goods and services including transportation, education, health care, wholesale and retail(Table 2), and food saw a significant decrease.

Manhattan Borough was found the most popular place all the time, even it experienced largest decrease in visit counts (Figure 3) during the outbreak of COVID-19.

This study identifies that the disparity in the human mobility during the COVID-19. People decrease their visits to low-income areas with relative high-poverty rate (Figure 4) such as Upper Manhattan (Figure 3), which indicates the business in these neighborhoods were hit hardest during the first month of the COVID-19.

In addition, bottom-income groups tend to have more visits to low-income and low education attainment areas such as Upper Manhattan Borough, Bronx Borough and Brooklyn Borough according to Figure 5. These areas have high poverty rate (Figure 4) and were found the most confirmed virus cases in March 2020(Buchanan et al., 2020).

On the other hand, top-income groups have more visits to Lower Manhattan, Staten Island (Figure 5), which are high-income and high education attainment areas. There was even a significant increase in Staten Island and outskirt of southeast shore of Brooklyn and north end of Queens Borough in March 2020 (Figure 6). Since these places have high vacancy rate (Figure 4) with low confirmed case rate in the first month(Buchanan et al., 2020), we can conclude that top-income groups migrated to outskirt of the city during the outbreak of COVID-19.

In addition, bottom-income groups of people was found have more smaller decrease degree of visit counts during the outbreak of COVID-19 and larger decrease degree after COVID-19 compared to top-income groups. Particularly, bottom-income people have smaller decrease to visit count of food, health care, wholesale and retail, transportation and education POIs in the first month of COVID-19. This indicates bottom-income people need to leave home to purchase necessary goods, services and work to secure thier daily living.

All the information indicates that bottom-income people suffer larger economic loss and higher risk of COVID-19 transmission during the onset of COVID-19. This exposes the social inequity issues in NYC.

This study has limitation in data representativeness. The anonymized device-based data from SafeGraph only captures visits from people using mobile phone and enabling the APP to upload GPS

information (SafeGraph, 2019). Also, SafeGraph determines the home census block groups of each devices by analyzing the most common location between 6pm and 7 am in 6 weeks(SafeGraph, 2022). Thus, this dataset may record people nighttime activities at public places as home erroneously. Multi-source human mobility analysis needed to be conducted to illustrate the spatio-temporal heterogeneity in human mobility comprehensively(Noi et al., 2022).

6 Reference

Johns Hopkins Coronavirus Center (2022). https://coronavirus.jhu.edu/map.html.

United States Census Bureau (2020). https://www.census.gov/quickfacts/newyorkcitynewyork.

Cordes, J., Castro, M. C. (2020). Spatial analysis of COVID-19 clusters and contextual factors in New York City. Spatial and Spatio-temporal Epidemiology, 34, 100355.

Sevtsuk, A., Hudson, A., Halpern, D., Basu, R., Ng, K., de Jong, J. (2021). The impact of COVID-19 on trips to urban amenities: Examining travel behavior changes in Somerville, MA. PloS one, 16(9), e0252794.

MORAN, Patrick AP. Notes on continuous stochastic phenomena. Biometrika, 1950, 37.1/2: 17-23.

Noi, E., Rudolph, A., Dodge, S. (2022). Assessing COVID-induced changes in spatiotemporal structure of mobility in the United States in 2020: a multi-source analytical framework. International Journal of Geographical Information Science, 36(3), 585-616.

Larry Buchanan, Jugal K. Patel, Brian M. Rosenthal Anjali Singhvi (2020). A Month of Coronavirus in New York City: See the Hardest-Hit Areas. The New York Times.

SafeGraph, Patterns https://docs.safegraph.com/docs/monthly-patternsgeographic-bias