A Spatial Analysis of Geographic Lessons from Past and Present Vaccination Programs

Background

Vaccinations are the key intervention used to limit the spread of infectious disease in public health spheres. In the current world landscape, a vaccine will be the most powerful weapon to limit COVID-19's impact. In the past, many diseases have had vaccinations produced to curtail their spread. Even though vaccines may take years to develop, these diseases will often not be eradicated. One such disease is poliomyelitis (polio). Although it has been documented by many sources for the burden of the disease and is not a disease that the western world has, it is still present in the global scene. In 1988 there were an estimated 350,000 cases, but only 33 as of 2018.(*Poliomyelitis*, n.d.) This decrease was mostly thanks to the Global Polio Eradication Initiative (GPEI), a coordinated vaccination program led by the WHO.(Aylward & Tangermann, 2011) Studying the factors that led for this massive decrease is important if we are to engage in mass distribution of a vaccine in the very near future.

Vaccinations work through the process of herd immunity. There is a threshold percent (HIT) of the population that needs to be immune so that an infectious individual will not pass on the disease to enough people to start an outbreak(Plans-Rubió, 2012a). For polio, the HIT is 80-86% of a population(Plans-Rubió, 2012a). Plans to distribute vaccines are full of scientific terminology and expertise; relaying this information effectively to the public is essential to a vaccine program (Plans-Rubió, 2012a). In 2005, there were only 4 countries where polio was considered endemic (Plans-Rubió, 2012a). One of the main issues with the GPEI was that it was thought that there was a lack of funding for these countries. In this paper, we will be examining the validity of those claims, and where there seemed to be a lack of funding. Armed with this knowledge, future vaccination programs can focus their funding efforts on areas that lacked the most in this program.

As the United States was among the highest rates of vaccination in 1988, at 97% this analysis will not benefit the United States and other high-income countries in the same manner. Within the United States, the areas that were the hardest hit were areas of high population density(*COVID-19 United States Cases by County*, n.d.). During the 1918 Pandemic influenza, districts that were below a specific threshold experienced population loss at a lower level than districts above the threshold (Chandra et al., 2013). There is also evidence to show that seasonal influenza epidemics are effected by urbanization (*Urbanization and Humidity Shape the Intensity of Influenza Epidemics in U.S. Cities | Science*, n.d.). As the most recent flu vaccination estimates are on the state level, this paper will also analyze how the density of the population at a state level affects the vaccination rate. This is an important scale to analyze because areas that are more population dense should have high vaccination rates to account for the contacts/time variable in the HIT calculation. Vaccination will help to prevent the spread of disease through limiting the number of people who are susceptible to the disease, without having to compromise the contacts/time that is associated with normal urban behavior (*Vaccination and Herd Immunity to Infectious Diseases | Nature*, n.d.). With or without this association, scientists and public health officials can estimate what scale vaccination programs need to be rolled out to be most effective with low levels of vaccine available.

Methodology

The data were sourced from various databases. Polio vaccination data was sourced from the WHO database. The World Bank Income (GDP) data was sourced from the World Bank Open Database. The US state population data was sourced from the US Census Bureau. The area of each state was sourced through ESRI and the US Census bureau. The US state flu vaccination rate data was sourced through the US CDC database.

For the analysis of polio vaccination and income level, vaccination cut points were decided using the HIT calculations of 80-86% vaccinated, and when each World Bank Income Group (WBIG) reached the predetermined HIT. Initial prevalence of vaccination was shown in 1980, High income group in 1983 met the HIT, Upper-middle group met the HIT in 1988, the lower-middle income group met HIT in 2014, and the lower middle-income group has never met the HIT. The income group and world map data were joined to allow for mapping. This will result in the creation of 4 bivariate choropleth maps. The first variable separated into categories of vaccination rate (0-30, 30-60, 60-80, 80+), and the second variable the four levels of World Bank income group (High, Upper-Middle, Lower-Middle, Low Income). This data was then analyzed

For the analysis of flu vaccination and population density, vaccination cut-points were decided using the standard deviations from the mean flu vaccination value (-2, -1, 0, 1, 2) for analysis. These were mapped at -2, 0, 2 standard deviations from the mean. The data were joined together and then to the US state tiger files. A field was added to create the population density, the population of the state divided by the total area. Total area was chosen because of the ability to live on houseboats or have property on islands that may not have been mapped correctly in the Tigerfile. For the statistical analysis, a linear regression was run to determine if there was a correlation between estimated vaccination rate in the state and the population density of the state.

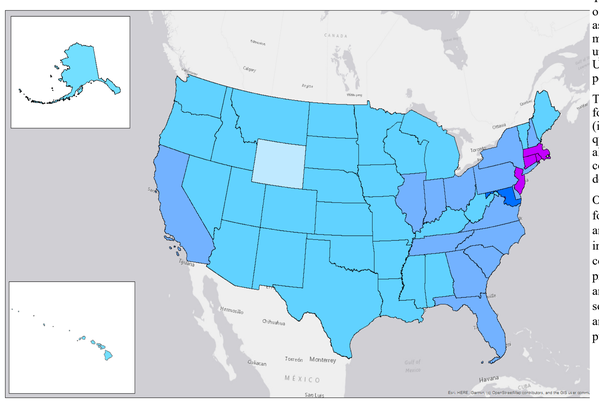
POPULATION DENSITY

IS THERE A HIGHER RATE OF FLU VACCINATION IN AREAS OF HIGH POPULATION DENSITY IN THE US?

Results

In the United States, states that have high population density also tend to have high vaccination rates. Only 5 units (4 states and Washington D.C.) were categorized to have high population density and all 5 of these units also had a high vaccination rate. The middle of the United States has a low population density, but the vaccination rate was variable. There were no states that had both a low population density and a high vaccination rate. Among states that had a mid-range population density, there were no statistically low vaccination rates. Indeed, there was only 1 state (Wyoming) that had a significantly low vaccination rate. As the population density was highly skewed to the right, population density could not be considered significant. The ordinary least square spatial analysis resulted in only Massachusetts having a significant relationship between population density and vaccination rate, as every other state resulted with a standard deviation of between ± 2.5 of the calculated coefficients.

Bivariate Population Density and Child Flu Vaccination Rates by US State 2018-2019 Flu Season



The bivariate relationship here is shown through the color gradient. The lighter the tone of the color, the lower the vaccination rate. As the color gradient shifts from blue to purple, the population density gets higher. As you can see here, the middle of the country has a low population density, and the east coast is the most densely populated. However, vaccination rates are higher in multiple geographic locations.

Discussion

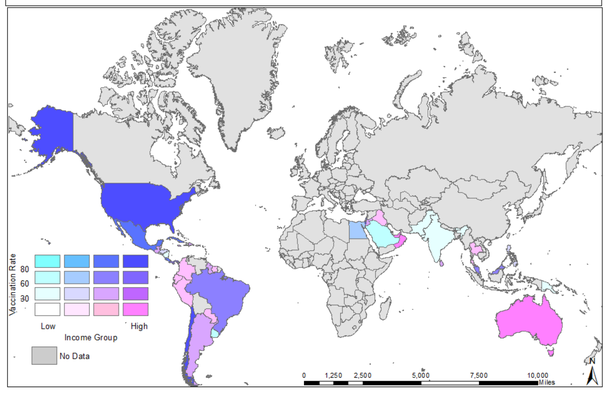
This hypothesis was based on the trends of infectious disease that are currently being analyzed. Social distancing is a practice that works by limiting the number of contacts/time, artificially decreasing the reproductive number of a pathogen. This reduction in the reproductive number decreases the herd immunity threshold (HIT), making it more viable for a population to have a decreased burden. This burden can be in many forms, depending on the severity of the disease. Pertaining to this analysis, the flu has a vaccine, but the effectiveness of the vaccine waivers yearly. This has multiple effects on the uptake of the vaccine that can skew the vaccination rate. Some studies have found that there are fears of side effects, and that uptake of the vaccine is not necessary among the general population(Böhmer et al., 2012). While population density might serve as one of the implicit factors in the environment of an individual when they decide to receive a vaccine, it may also serve as a collinear factor for increased exposure to positive messaging surrounding a vaccine, which are often placed in spaces of transportation and/or commute. Urban areas tend to have a higher ratio of physicians:population, thus increasing access to services (Shipman et al., 2011) This increase in access may lead to an increase in the recommendations of a physician for an individual to receive a vaccine (the CDC lists provider recommendations as a standard of practice).

The strengths of this analysis lie in its ability to connect multiple layers of the vaccination uptake debate. The population density seems to be associated with the vaccination rate, on the large scale, as seen on the map. This map is also using recent data, showing that the vaccine uptake is not as high as it should be, as these numbers fall short of the US recommended vaccination percentage of 80% for general population and 90% for high-risk persons (Plans-Rubió, 2012).

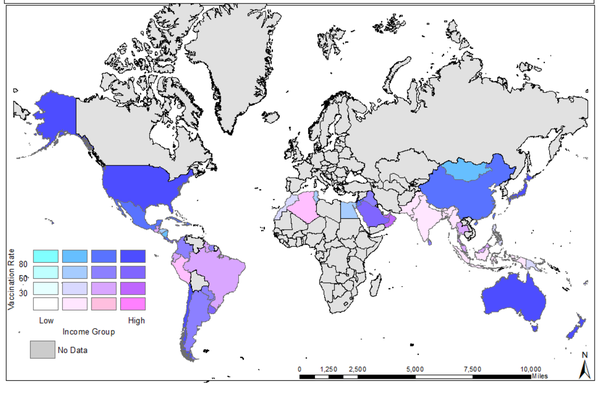
This analysis is not without its limits. Firstly, the method of calculation for the population density did not lend to normally distributed data (indicated by the heavy skew), the estimated correlation is questionable and warrants further investigation. The flu data here is also not granular. If the flu vaccination rates were reported at the county level, this analysis would be much more reliable, as population density is a much more accurate predictor at smaller levels.

Overall, this section of the analysis shows that there needs to be a focus on the Midwest for vaccination uptake, most likely in the cities and urban centers, where there is likely to be infrastructure for this intervention. Research should continue to delve deeper into the connections between vaccination rate and population density, as protecting dense populations is the key to protecting the rural areas that are traditionally less open to vaccination. Research should focus on social factors that lead to low vaccination rates and compare how they are related to population density to tease out where policies should be put in place to address concerns and fears surrounding vaccination.

World Bank Income Group (by GDP in 2020) and Polio Vaccination Rate in 1980



World Bank Income Group (by GDP in 2020) and Polio Vaccination Rate in 1984



INCOME

IS THERE AN ASSOCIATION BETWEEN THE GROSS DOMESTIC PRODUCT OF A COUNTRY, AND THE TIME TO REACH THE HERD IMMUNITY

Results

In the first map, on the top left, there are a total of 53 countries with polio vaccination and World Bank Income Group (WBIG) data (complete data). In the second map, of 1984 on the bottom left, there are a total of 67 countries with complete data. In the third map, of 1988 on the top right, there are a total of 70 countries with complete data. In the fourth map, of 2014 on the bottom right, there are a total of 82 countries that have complete data.

These maps show snapshots of the years where an entire WBIG meets the HIT for polio, a vaccination rate of 80%. In 2020, South America is classified in multiple different income groups. However, the vaccination rates in this section of the globe have drastically changed in the past 40 years. Most countries had a below 60% vaccination rate in 1980, and in 2020, almost all have above the 80% threshold. As a trend, the entire world improved their vaccination rate. There was a consistent 4 year gap between the top 2 WBIG reaching he HIT. There was a span of 26 years from when the Upper Middle WBIG reached the HIT to when the Lower Middle WBIG reached the HIT, and the Low Income WBIG has yet to reach the HIT as a group.

The linear regression showed that compared to the High Income Group, the other 3 groups were expected to have lower vaccination rates. In the case of the Low Income, 30 percentage points lower. High income countries were expected to have a vaccination rate of 90.5%, with Upper Middle Income at 83.9 %, Lower Middle Income at 74.4 and low at 60% in any year between 1980 and 2020. These were all significant below the .0001 level.

Discussion

The European and African data is not present on these maps. The source of the data did not have any European or African statistics, and these statistics were not easily accessible, so this map suffers from a lack of data. What would be useful for politicians would be to set up channels for quick, easy and understandable data transfer. During times where there needs to be quick data exchange to react properly to outbreaks, and use funding effectively, these channels become increasingly important. This trend may not be apparent at first glance, but this is a hypothesis that should be investigated further. If it is indeed true that data sharing is a concept that is lacking avenues in low income countries, it will be pertinent to more than just one infectious disease. Having a platform used for data sharing in this setting will make addressing these diseases much easier in the future.

A strength of this map is the trends that it shows. Polio vaccination increased, indicating that the GPEI worked, and there are lessons to be learned from the policies and fixes that were in place. This analysis seems to agree with findings from the literature that argue funding was a source of weakness in the GPEI. As countries that had low income, as measured by the world bank, were found to have a lower vaccination rate, more investigation into this trend is required. This could be because of a multitude of factors, lack of funding may cause not enough vaccines to be distributed, disruptions in the cold chain of vaccine storage, or less adequate ratios of providers: patients.

Most weaknesses of this analysis stem from the lack of data. While it shows that there isn't a defined channel within this organization for data communication and dissemination, that does not mean the data does not exist. However, the data that is missing limits the accuracy of this analysis. This may not account for some of the trends that were present in the early 2000s in Sub-Saharan Africa, and will weaken the correlation among High and Upper Middle Income countries because of the absence of the European Union. Additionally, this data does not count for the movement between WBIG that has occurred recently and in the past. This will also change the estimates and correlations from among groups, as countries are able to fund their own programs to a higher degree with increased GDP and financial influence. As a recommendation for policies, this analysis suggests that it is beneficial to increase funding and data capacity in low income countries so that the burden of disease can be quantified, and then appropriate measures for prevention and treatment can be taken.

Citations :

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Population Density Analysis Projection:: Lambert Conformal Conic

Income Analysis Projection: World Mercator

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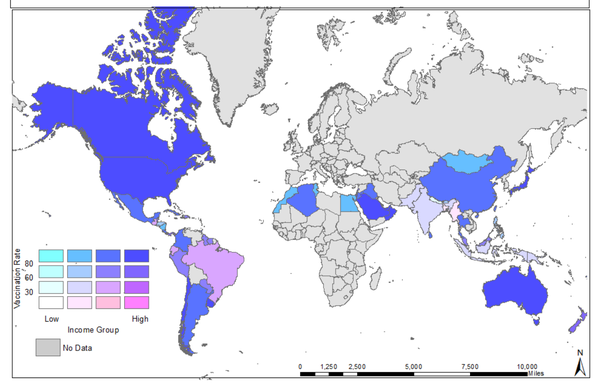
World Bank Income Group (by GDP in 2020) and Polio Vaccination Rate in 1988



World Bank Income Group (by GDP in 2020) and Polio Vaccination Rate in 2014