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Article

Has COVID-19 Affected DTP3 Vaccination in the Americas?

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Abstract: Background: In America, vaccine-related deaths constitute a significant contributor to child mortality. An essential means of reducing this is through broad vaccine coverage. The COVID-19 pandemic has posed a potential disruption to vaccine coverage due to its effects on the healthcare system. Objectives: This study aims to evaluate the impact of the COVID-19 pandemic on DTP3 vaccination coverage in the Americas, investigating trends from 2012 to 2022 to identify significant changes, regional disparities, and the overall effect of the pandemic on progress towards global immunization targets. Methods: This study used the coverage data for the third dose of the Diphtheria, Tetanus, and Pertussis Vaccine (DTP3) pulled from UNICEF databases spanning 2012 to 2022. We conducted a JoinPoint regression to identify points of significant trend changes. The annual percentage change (APC) and 95% confidence intervals (95% CI) were calculated for America and its regions. We also used segmented regression analysis. Using the Chi-square test, we compared DTP3 vaccination coverage for each country between 2019 and 2022. Results: Overall, America saw a decrease in vaccine coverage during this period, with an APC of -1.4 (95% CI -1.8; -1.0). This trend varied across regions. In North America, the decrease was negligible (-0.1% APC). South America showed the steepest decrease, with an APC of -2.5%. Central America also significantly declined, with an APC of -1.3%. Our findings suggest a concerning trend of declining DTP vaccination rates in the Americas, exacerbated in certain regions, in the wake of the COVID-19 pandemic. The absolute decrease in vaccine coverage in the Americas was -4 % between 2019 and 2022, with the most significant drop observed in Central America (-7 %). However, six countries reported increased vaccination rates post-COVID-19, led by Brazil, with a 7% increase. Conversely, twenty-two countries registered a decline in DTP3 vaccine coverage, with the average decrease being -7.37%. This decline poses a significant challenge to achieving the WHO's target of 90% coverage for the third dose of DTP by 2030, as evidenced by the reduction in the number of countries meeting this target from 2019 to 2022. Conclusions: The COVID-19 pandemic has impacted vaccine coverage in America, leading to a decrease, especially across Central America.

Keywords: DTP vaccine; america; COVID-19; vaccine coverage; joinpoint regression; health care system; vaccination rates; trends; segmented regression

1. Introduction

Immunization is a cornerstone in public health, pivotal in diminishing the prevalence and severity of infectious diseases and their effects on health outcomes[1–3]. Vaccine-preventable diseases remain a significant public health concern globally. Diphtheria, Tetanus, and Pertussis (DTP) vaccines prevent these life-threatening diseases, especially among children. The DTP vaccine's broad coverage is imperative for public health protection. However, the COVID-19 pandemic, emerging in early 2020, posed significant challenges to healthcare systems globally[4], potentially impacting routine immunization services, including DTP vaccination. Programs emphasizing immunization, especially those incorporating the DTP vaccine, are central to reducing the worldwide incidence of diseases preventable by vaccines, thereby improving the lives of countless individuals[5–8]. The World Health Organization (WHO) launched in response to this global health challenge, the Global Vaccine Action Plan (GVAP) for the period 2011–2020, initiated in 2012, to achieve widespread routine immunization for children across the globe[9]

Child mortality due to vaccine-preventable diseases is a significant concern, with pertussis alone accounting for over 300,000 deaths annually[10]. Factors influencing disparities in vaccination rates include geographic location (urban vs. rural), socioeconomic status, educational level [11,12] and the regularity of maternal prenatal care[13]. Parents in rural areas believe vaccine-preventable diseases (VPD) are not severe enough to justify vaccination[14]. The emergence of the COVID-19 pandemic has placed an extraordinary burden on global healthcare infrastructures, potentially impacting the continuity of standard immunization efforts[15–20]. Disruptions in the supply chain of vaccines, the redirection of healthcare resources and personnel to COVID-19 management[21], the logistic challenges of COVID-18 immunization[22], and heightened public reluctance to visit medical facilities due to infection risk have all been implicated in the observed decrease in vaccination rates[23–28]. Such a downturn in immunization coverage poses a severe risk to millions of children, leaving them vulnerable to diseases preventable by vaccines[29]. The pandemic has increased the likelihood of outbreaks of VPD [12]. Lower-middle-income regions with low vaccine coverage and circulating vaccine-derived viral strains, such as polio, bore an additional burden of zero-dose children. All over the world, there were 18.2 million zero-dose children in 2021[30] that are more vulnerable to VPDs.[12] Understanding the extent of this disruption is crucial to guide public health policies and strategies for crisis preparedness[31]. Research has shown a global decline of 7.7% in DTP3 coverage and 7.9% in MCV1 (first dose of Measles-Containing Vaccine) coverage up to December 2020[32].

In assessing the success of DTP vaccination programs, we focus on the proportion of infants receiving DTP3, a standard and widely recognized metric[33]. This indicator reflects the effectiveness of the immunization programs in reaching target demographics and completing the primary vaccination series, providing optimal protection against diphtheria, tetanus, and pertussis[34]. The analysis of both DTP1 and DTP3 coverages is essential, with DTP1 coverage indicating the initial reach and engagement of health services [35,36] and DTP3 demonstrating the success in administering the entire course of the vaccine[37]. For instance, a meta-analysis highlighted a significant dropout rate in vaccinations in Africa, with notable variations between countries [35,36]. Discrepancies between DTP1 and DTP3 coverages can shed light on challenges in patient retention and other barriers such as healthcare access, affordability, and education[37]

Two countries in America were included in the Immunization Agenda 2030 in 2021: Brazil was ranked seventh, and Mexico in 15th. In 2022, Mexico disappeared from the list, and Brazil descended to the eighth position[38].

The pandemic's disruption had widespread implications for DTP vaccination coverage. Healthcare resources were reallocated to address the pandemic, leading to the neglect of routine vaccination programs. Social distancing and lockdowns are public health measures that may have hindered access to vaccination services. Moreover, the pandemic could have affected public perception and confidence in vaccines, further challenging vaccination efforts. In the United States, during the pandemic, there was a decrease in pediatric primary care visits[39]. Recent data points to a substantial impact of the COVID-19 pandemic on DTP vaccination trends[40]. A significant decline

in administered doses of DTP-containing vaccines was observed in the first half of 2020. This trend was not limited to specific regions but was a global phenomenon with varying degrees of impact across various parts of the world. In Africa, for instance, there was a notable decrease in DTP3 coverage post-2019[41].

Similarly, a decline in vaccination coverage for multiple vaccines was observed in Latin America, with catch-up strategies implemented to address missed vaccinations[42]. Reports from WHO and UNICEF indicate a notable global decrease in child vaccinations, with DTP3 coverage falling by 5% between 2019 and 2021[30]. The CDC's 2021 data confirms this trend, showing the lowest global DTP3 coverage since 2008[43]. From 2021 to 2022, there was a notable increase in global vaccination coverage for the first dose of the DTP vaccine, from 86% to 89%, and measles-containing vaccine, from 81% to 84%. However, these levels did not return to the pre-pandemic coverage rates of 90% and 86%, respectively. Despite the challenges of the pandemic, there have been signs of recovery. By 2022, global DTP immunization coverage nearly returned to pre-pandemic levels, although millions of infants still lacked initial or complete vaccination[35,44]. This recovery highlights the resilience of health systems and the importance of ongoing assessment and implementation of catch-up vaccination strategies, particularly for vulnerable populations, to ensure vaccine coverage equity and health system resilience. This recovery in vaccination coverage was uneven across different regions and countries, with slower progress in low-income countries[45]. This data, part of the World Health Assembly's endorsement of the Immunization Agenda 2030 (IA2030), highlights the ongoing challenge of restoring and improving global vaccination coverage after the COVID-19 pandemic, particularly among low- and lower-middle-income countries[46].

This study aims to analyze the trends in DTP3 vaccination coverage in America from 2012 to 2022, emphasizing the influence of the COVID-19 pandemic. Based on the evidence discussed, we posit that the pandemic has adversely affected vaccination rates [43,46].

Considering the available data, we observe a significant global impact of the COVID-19 pandemic on DTP vaccination trends. Reports from WHO and UNICEF highlight a worldwide decline in child vaccinations during this period[47]. The risk for children in developing vaccine-preventable diseases is thus elevated. This study aims to assess the impact of the COVID-19 pandemic on DTP vaccination coverage in the Americas. We hypothesize that the pandemic has led to declining vaccination rates, potentially reversing previous progress toward global immunization targets. This paper examines trends in DTP3 vaccine coverage across the Americas from 2012 to 2022, identifying significant changes and regional disparities considering the pandemic. The findings aim to provide a detailed understanding of the pandemic's impact on DTP vaccination and guide public health strategies to address these challenges, ensuring continued progress towards global vaccination goals. We will focus primarily on the repercussions of the COVID-19 pandemic under the hypothesis that pandemic-related disruptions have affected vaccination programs[43].

2. Materials and Methods

Vaccination rates for each country were extracted from the UNICEF databases, covering 2012 to 2022 [48]. We excluded the following territories: French Guiana, Greenland, Alaska, Anguilla, Aruba, Bermuda, Bonaire, Curaçao, and Guadeloupe. We also obtained regional estimations from the UNICEF database [48]. The data on the number of newborns per country per year was sourced from the UNICEF database[49]. Population figures for the respective countries and years under study were obtained from the World Bank. [50]

2.1. Regional analysis

In an analysis focusing on DTP3 vaccination in the Americas, regional data for South America, Central America, and the Caribbean were computed using vaccination rates population-weighted calculations due to the absence of specific regional information from UNICEF. The countries included in each region were as follows: North America included Canada, Mexico, and the United States. Central America included Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama. In the Caribbean, the study encompassed Antigua and Barbuda, Bahamas, Barbados, Cuba,

Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, and Trinidad and Tobago. For South America, the countries analyzed were Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, and Venezuela. This method of calculating data, based on the population of each country, was essential for deriving accurate estimations of DTP3 vaccination coverage in these regions. This approach ensured a comprehensive and representative analysis of DTP3 vaccination coverage across the diverse regions of the Americas.

2.2. Statistical analysis

We employed JoinPoint regression analysis for a widely recognized method for analyzing regional and country trends and detecting changes in various data types. Using this method allowed us to detect periods of sustained changes in incidence rates and quantify the magnitude of change in each trend. Joint point regression is a statistical technique that detects points where there is a change in the trend, the so-called "joinpoints." It has been used to study the evolution of vaccinations[41]. Using joint point regression, the annual percentage change (APC) and 95% confidence intervals were estimated to quantify the magnitude of change in each trend. In these models, the vaccine coverage was the dependent variable, while the year was the independent variable. We used the Durbin-Watson to assess the existence of autocorrelation in the time series data [51].

We also used an interrupted time series analysis. Interrupted time series analysis is the most robust quasi-experimental approach for evaluating external events such as the COVID-19 pandemic or interventions[52–54]. In our study, there were eleven years, seven years 2012–2019 preCovid, and three years, 2020–2022, post-Covid. The model of the analysis follows the following equation.

$$DTP3t = \beta_0 + \beta_1 Y_t + \beta_2 P_t + \beta_3 Y_t P_t + \varepsilon_t \quad (1)$$

Where DTP3t is the number of DTP3 doses administered at year t, Y_t is a variable indicating the year of the observation period (2012–2022). P_t is a dummy variable indicating Pandemic at time t coded as "0" for the periods before COVID-19 (2012–2019), and "1" is the code for the period after COVID-19 (2020–2022); $Y_t P_t$ is an interaction term between the time and COVID-19 dummy. ε_t is the error term, β_0 estimates the baseline level DTP3 at the beginning of the period, β_1 estimates the change in the number of DTP3 vaccinated children until the start of the COVID-19 pandemic, β_2 is the change in the DTP3 number of vaccinated children after the COVID-19 pandemic, and β_3 is the difference in the trends of DTP3 vaccinated children before and after the pandemic (effect of COVID-19 during the pandemic).

We also compared the DTP3 vaccination coverage for each nation in 2019 and their corresponding coverage figures in 2022. Paired sample tests were used to compare DTP coverage between 2019 and 2022. We evaluated the DTP3 vaccination coverage in America by country, comparing the coverage rates across different countries for 2019 and 2022. We used the Chi-Square test, wherein the coverage rates were weighted by the number of newborns in each country for the respective year.

2.3. Software

All joint point computations were done with Joinpoint Regression software (Joinpoint Regression Program, Version 5.0.2. May 2023; Statistical Research and Applications Branch, National Cancer Institute)[55,56]. The statistical analysis comparing rates from 2019 to 2022 used IBM SPSS Statistics, version 27 (IBM Corp., Armonk, NY, USA). The interrupted time series analysis was computed as a 'segmented' [57–60] package in R (version 4.3.1, 2023-06-16 ucrt)[61], under Rstudio (Version 2023.09.1 Build 494)[62]. This was complemented using the 'ggplot2' package for advanced graphical representations[63] and the 'readxl' package for seamlessly importing Excel data files[64]. Maps were created with Mapchart (v 4.3.2.)[65]. The scale of colors for the maps was elaborated with Colorbrewer (v.2.0)[66,67].

3. Results

Between 2012 and 2021 in the Americas, the third dose DTP vaccination rates displayed an overall annual percentage change (APC) of -1.4%. This decline was statistically significant, with a 95% confidence interval (CI) ranging from -1.8 to 1.0 and a p-value of less than 0.001. The JoinPoint analysis identified two distinct periods within this period. From 2012 to 2016, the APC was -0.7% during the first period, indicating a slight decrease, but this change was not statistically significant (95% CI: -2.9 to 1.5; $p=0.464$). In contrast, a marked decline was observed in the second period, from 2016 to 2022, where the APC steepened to -1.8% (95% CI: -2.9 to -0.7) with a p-value of 0.008, indicating a significant downward trend. These findings suggest a shift in the trajectory of vaccination rates over the decade, with a notable decline in the latter half of the period (Table 1, Figure 1).

Table 1. Joinpoint analysis for the third doses DTP vaccination rates in the Americas, 2012–2022.

Periods	Years	APC (95% CI)	P
Total Period	2012-2021	-1.4 (-1.8; -1.0)	< 0.001
Period 1	2012-2016	-0.7 (-2.9; 1.5)	0.464
Period 2	2016-2022	-1.8 (-2.9; -0.7)	0.008

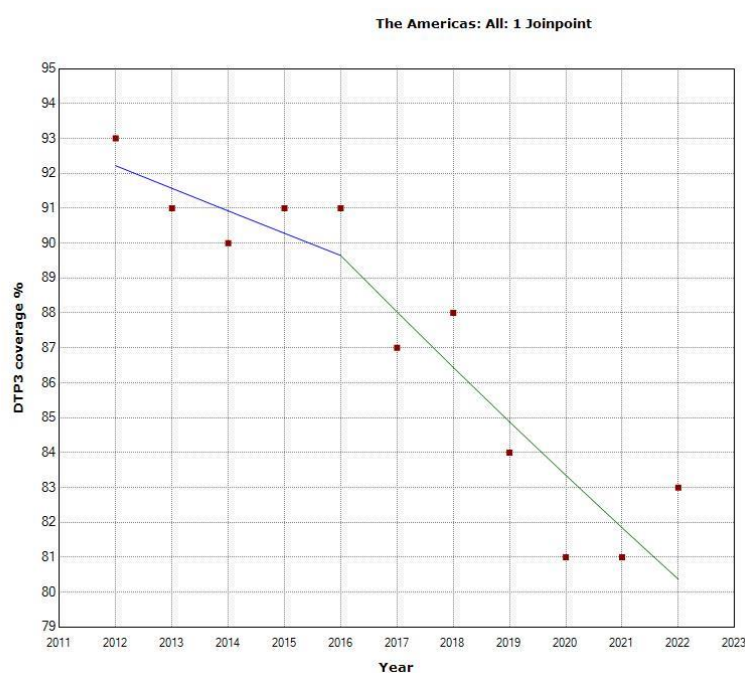


Figure 1. Third DTP doses vaccination rate trends in the Americas (2012-2021) indicating joinpoints.

The JoinPoint analysis for regional third DTP dose coverage in America from 2012 to 2022 reveals varied trends across different regions. In North America, the overall annual percentage change (APC) for the total period was -0.1% (95% CI: 0.2 to 0), indicating a negligible decrease in vaccination rates. (Table 2), The change was not statistically significant ($p=0.136$). There was JoinPoint in 2014. From 2012-14, there was a slight increase; from then on, there was a decrease, as depicted in Figure 2.

Table 2. Joinpoint analysis for Regional 3rd DTP dose coverage in America, 2012–2022.

Periods	Years	APC	95% LCI	95% UCI	P
<i>North America</i>					
Total Period	2012-2022	-0.1	0.2	0	0.136
Period 1	2012-2014	0.6	-0.2	1.4	0.494

Period 2	2014-2022	-0.2	-0.9	0.1	0.057
<i>Latin America and the Caribbean</i>					
Total Period	2012-2022	-2.1	-2.7	-1.5	< 0.001
Period 1	2012-2016	-0.9	-4.4	2.6	0.531
Period 2	2016-2022	-2.7	-4.5	-0.9	0.010
<i>Central America</i>					
Total Period	2012-2022	-1.3	-2.1	-0.4	0.009
Period 1	2012-2019	-0.9	-2.8	1.1	0.321
Period 2	2019-2022	-2.6	-8.6	3.8	0.354
<i>Caribbean</i>					
Total Period	2012-2022	-0.7	-1.1	-0.4	0.001
Period 1	2012-2016	0.0	-1.9	2.0	0.996
Period 2	2016-2022	-1.1	-2.1	-0.1	0.031
<i>South America</i>					
Total Period	2012-2022	-2.5	-3.1	-1.8	< 0.001
Period 1	2012-2015	-0.3	-5.9	5.6	0.895
Period 2	2015-2022	-3.1	-4.4	-1.8	0.001

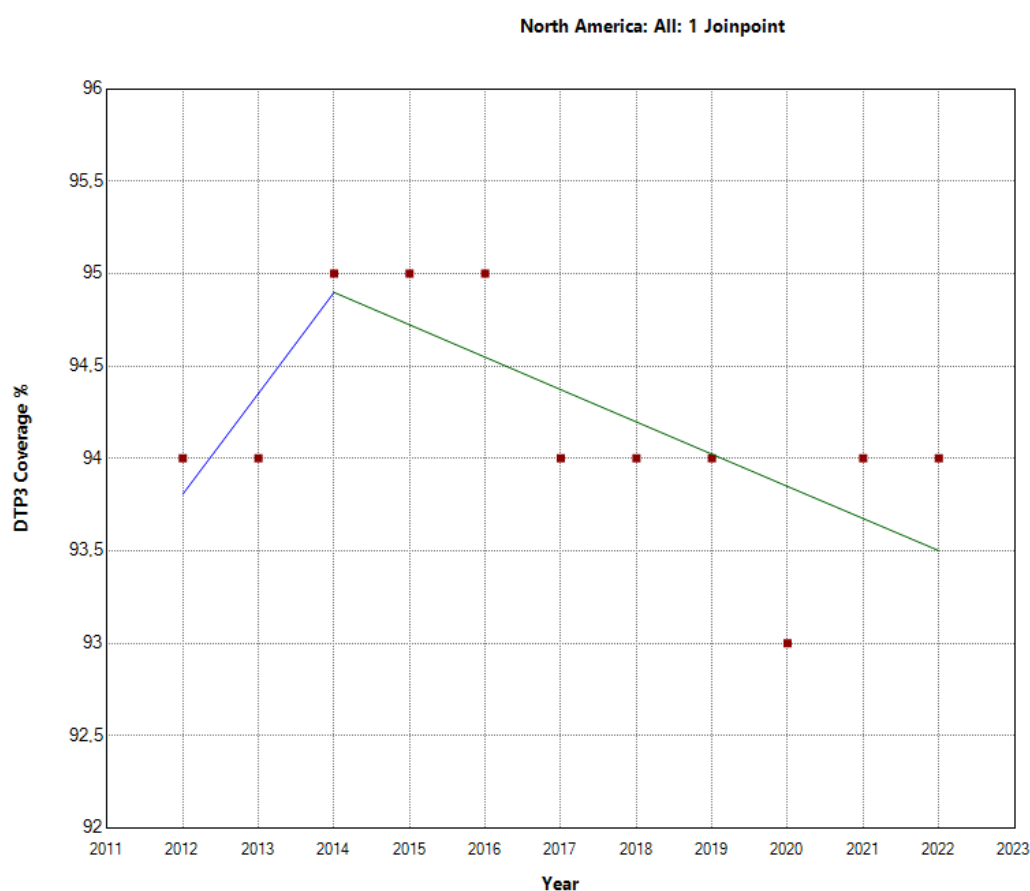


Figure 2. Third DTP doses vaccination rate trends (2012-2022): North America.

In contrast, Latin America and the Caribbean exhibited a more pronounced decline in vaccination rates. The total period APC was -2.1% (95% -2.7 to -1.5, with a statistically significant change ($p < 0.001$)). Further analysis within this region revealed a joint point in 2016. There were two distinct periods: the first period (2012-2016) showed an APC of -0.9%, which was not statistically significant (95% CI: -4.4, 2.6, $p=0.531$), indicating a stable trend. However, during the second period

(2016-2022), the decline in vaccination rates was more substantial, with an APC of -2.7% (95% CI: -4.5, -0.9, $p=0.010$), indicating a significant decrease in vaccination rates, as shown in Figure 3. These findings highlight substantial regional differences in third DTP dose coverage trends within Latin America and the Caribbean, which are visually depicted in Figures 4–6, illustrating the third DTP dose vaccination rate trends in Central America, the Caribbean, and South America, respectively, highlighting the joinpoints.

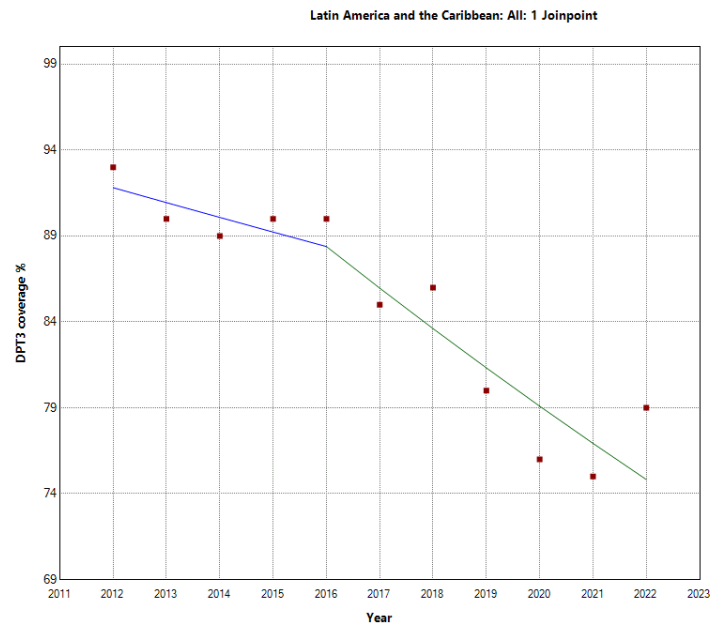


Figure 3. Third DTP doses vaccination rate trends in *Latin America and the Caribbean* (2012-2022) indicating joinpoints.

In the study period from 2012 to 2022, the trends in vaccination rates with the third dose of DTP varied significantly across regions in Central America, the Caribbean, and South America.

In Central America, the overall annual percentage change (APC) was -1.3% (95% CI -2.1, -0.4; $P=0.009$), with a statistically significant decrease noted. There was a JoinPoint in 2019. This region experienced a more pronounced decline in the latter period (2019-2022) with an APC of -2.6% (95% CI -8.6, 3.8; $P=0.354$), though this change was not statistically significant. (Figure 4)

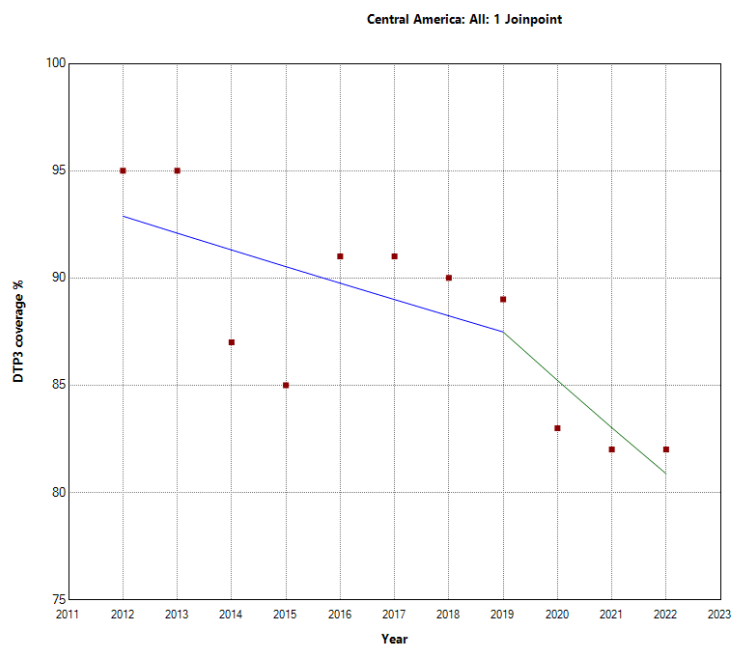


Figure 4. Third DTP doses vaccination rate trends (2012-2022) in Central America.

The Caribbean region showed a different pattern, with an overall decrease in the vaccination rate with an APC of -0.7% (95% CI -1.1, -0.4; $P=0.001$). There was a JoinPoint in 2016. This decrease became statistically significant in the second period (2016-2022), with an APC of -1.1% (95% CI -2.1, -0.1; $P=0.031$).

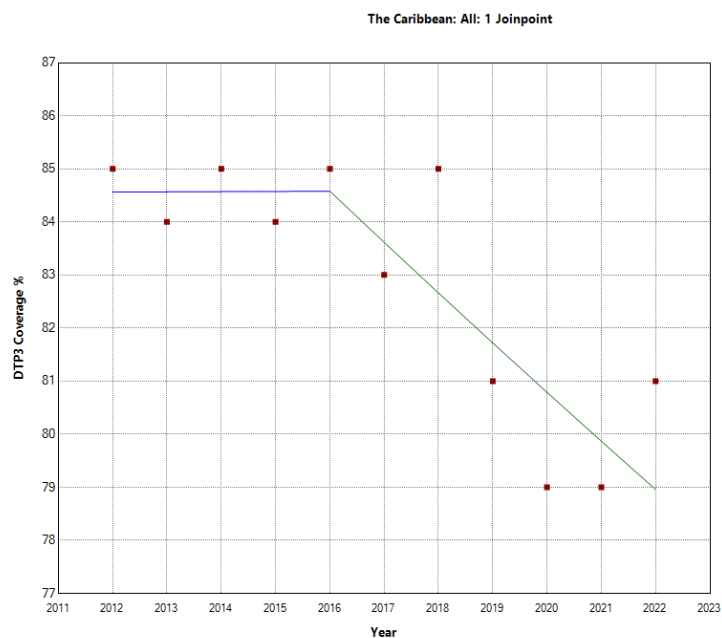


Figure 5. Third DTP dose coverage (2012-22) in the Caribbean indicating joinpoints.

In South America, the total period saw a significant decline in vaccination rates with an APC of -2.5% (95% CI -3.1, -1.8; $P < 0.001$). There was a JoinPoint in 2015. The trend intensified in the second period (2015-2022), with an APC of -3.1% (95% CI -4.4, -1.8; $P=0.001$).

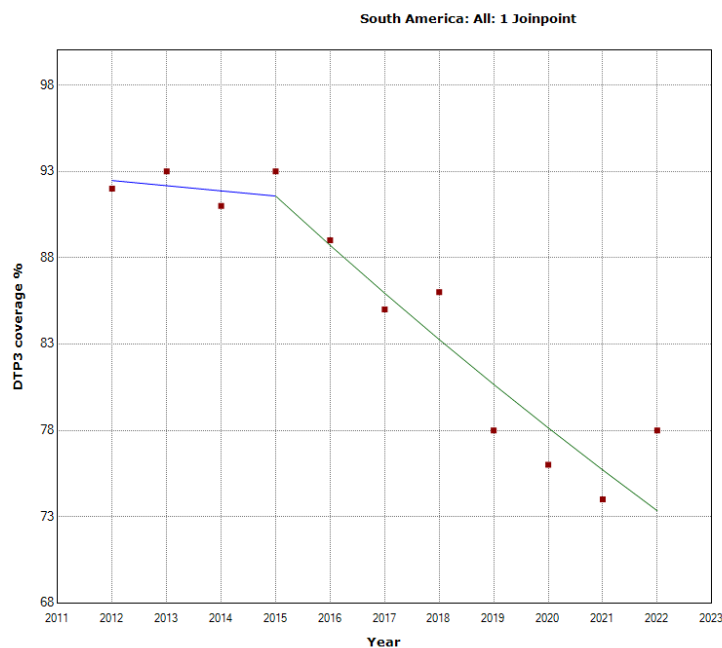


Figure 6. Third DTP dose coverage (2012-22) in South America indicating joinpoints.

These findings suggest region-specific variations within Latin America and the Caribbean region, with South America experiencing the most significant decline over the study period (Figure 5). The absolute decrease in vaccine coverage in America between 2019 and 2022 was -4%. The coverage remained equal in North America, South America, and the Caribbean, while the more significant decrease occurred in Central America with -7%. (Table 3)

Table 3. Absolute and Relative Changes in DTP Vaccination Coverage (%) Across American Regions between 2019 and 2022.

Region	2020		2022		Absolute Changes 2019-2022	Relative Changes 2019-2022
	2019	2021	2021	2022		
Americas	84	81	81	83	-1%	-1,19%
North America	94	93	94	94	0%	0,00%
Latin America and the Caribbean	80	76	75	79	-1%	-1,25%
South America	78	76	74	78	0%	0,00%
Central America	89	83	82	82	-7%	-7,87%
Caribbean	81	79	79	81	0%	0,00%

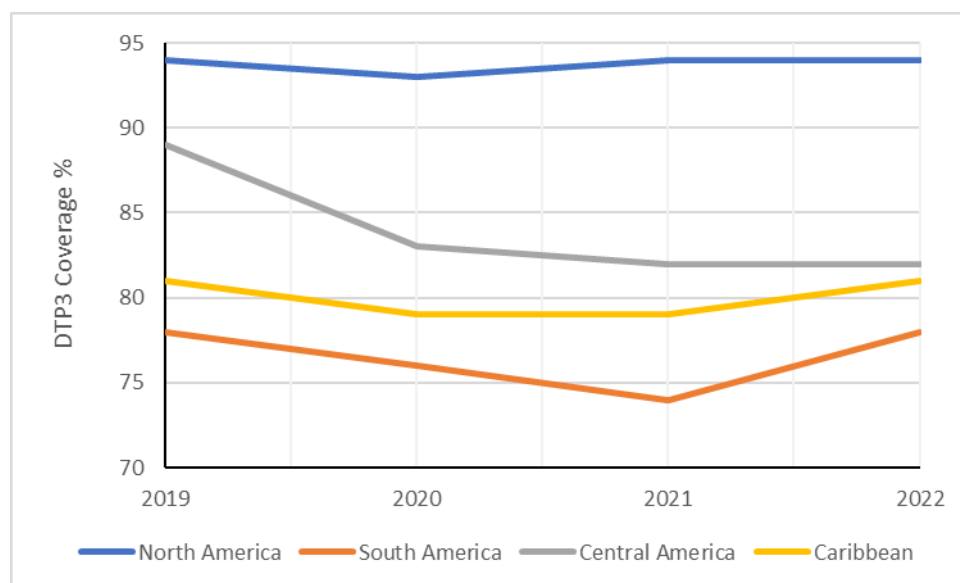


Figure 7. Evolution of Third DTP dose coverage (2012-22) in South America by Regions.

Table 4 presents the DTP third dose coverage in 2019 and 2022. The average country decrease was -4.20% (SD=6.08), $p < 0.001$. In Figures 8–10, we present the map of America indicating the absolute differences in vaccine coverage between 2012 and 2022. Between 2019 and 2022, the DTP3 vaccination rates showed a significant decline, as observed in the dataset, which revealed that twenty-two countries (61.1%) in America registered a decrease, while only six countries (16.7%) indicated an increase and 8 (22.2%) remained unchanged.

Table 4. Absolute and Relative Changes in DTP Vaccination Coverage (%) Across American Countries between 2019 and 2022.

Country	2020		2022		Absolute Changes 2019-2022	p*
	2019	2021	2021	2022		
Antigua and Barbuda	95	96	92	99	4.00%	<0.001
Argentina	83	74	81	81	-2.00%	<0.001
Bahamas	89	83	86	87	-2.00%	ns
Barbados	90	85	82	86	-4.00%	ns
Belize	98	79	83	84	-14.00%	0.003
Bolivia	75	68	70	69	-6.00%	<0.001
Brazil	70	77	68	77	7.00%	<0.001
Canada	91	92	92	92	1.00%	ns
Chile	96	93	95	96	0.00%	ns
Colombia	94	88	86	87	-7.00%	<0.001
Costa Rica	95	97	93	95	0.00%	ns
Cuba	99	99	99	99	0.00%	ns
Dominica	99	96	92	92	-7.00%	ns
Dominican Republic	89	82	84	88	-1.00%	ns
Ecuador	85	70	72	70	-15.00%	<0.001
El Salvador	90	76	78	75	-15.00%	<0.001
Grenada	94	72	77	77	-17.00%	0.054
Guatemala	85	83	79	79	-6.00%	<0.001
Guyana	99	99	98	98	-1.00%	ns
Haiti	51	51	51	51	0.00%	ns
Honduras	88	80	77	78	-10.00%	<0.001

Jamaica	96	96	90	98	2.00%	ns
Mexico	82	72	78	83	1.00%	<0.001
Nicaragua	98	92	87	92	-6.00%	<0.001
Panama	88	74	87	87	-1.00%	ns
Paraguay	86	79	70	69	-17.00%	<0.001
Peru	88	72	82	82	-6.00%	<0.001
Saint Kitts and Nevis	97	99	96	96	-1.00%	ns
Saint Lucia	92	86	80	81	-11.00%	ns
Saint Vincent and the Grenadines	97	97	92	92	-5.00%	ns
Suriname	77	51	72	77	0.00%	ns
Trinidad and Tobago	93	96	94	93	0.00%	ns
Uruguay	94	92	91	94	0.00%	ns
United States	94	93	94	94	0.00%	ns
Venezuela	64	54	56	56	-8.00%	<0.001

ns= no significant *Chisquare Test.

Although COVID-19 impacted vaccine coverage, six countries had increased vaccination coverage after the COVID-19 pandemic. Brazil led this trend with a notable 7% increase in coverage. Following Brazil, Antigua and Barbuda saw a 4% rise, while Jamaica experienced a 2% increase. Canada and Mexico also reported modest increases of 1% each.

Conversely, eight countries demonstrated stability in their DTP3 vaccine coverage during the same period. Countries such as Chile, Costa Rica, Cuba, Haiti, Suriname, Trinidad and Tobago, the United States, and Uruguay maintained their coverage levels, with no percentage change observed. However, the study also identified 22 American countries where there was a decline in DTP3 vaccine coverage (Argentina, Bahamas, Barbados, Belize, Saint Kitts and Nevis, Bolivia, Colombia, Dominican Republic, Ecuador, El Salvador, Dominica, Grenada, Saint Lucia, Saint Vincent and the Grenadines, Guatemala, Guyana, Honduras, Nicaragua, Panama, Paraguay, Peru, and Venezuela). The Dominican Republic, Guyana, Panama, Saint Kitts and Nevis experienced a 1% decrease, while Argentina faced a 2% decline. In countries where vaccination coverage decreased, the absolute decrease had a mean of -7.37% (SD = 5.39)($P < 0.01$). (Table 4) (Figures 8–10)



Figure 8. Absolute Changes in DTP Vaccination Coverage (%) Across American Countries between 2019 and 2020.

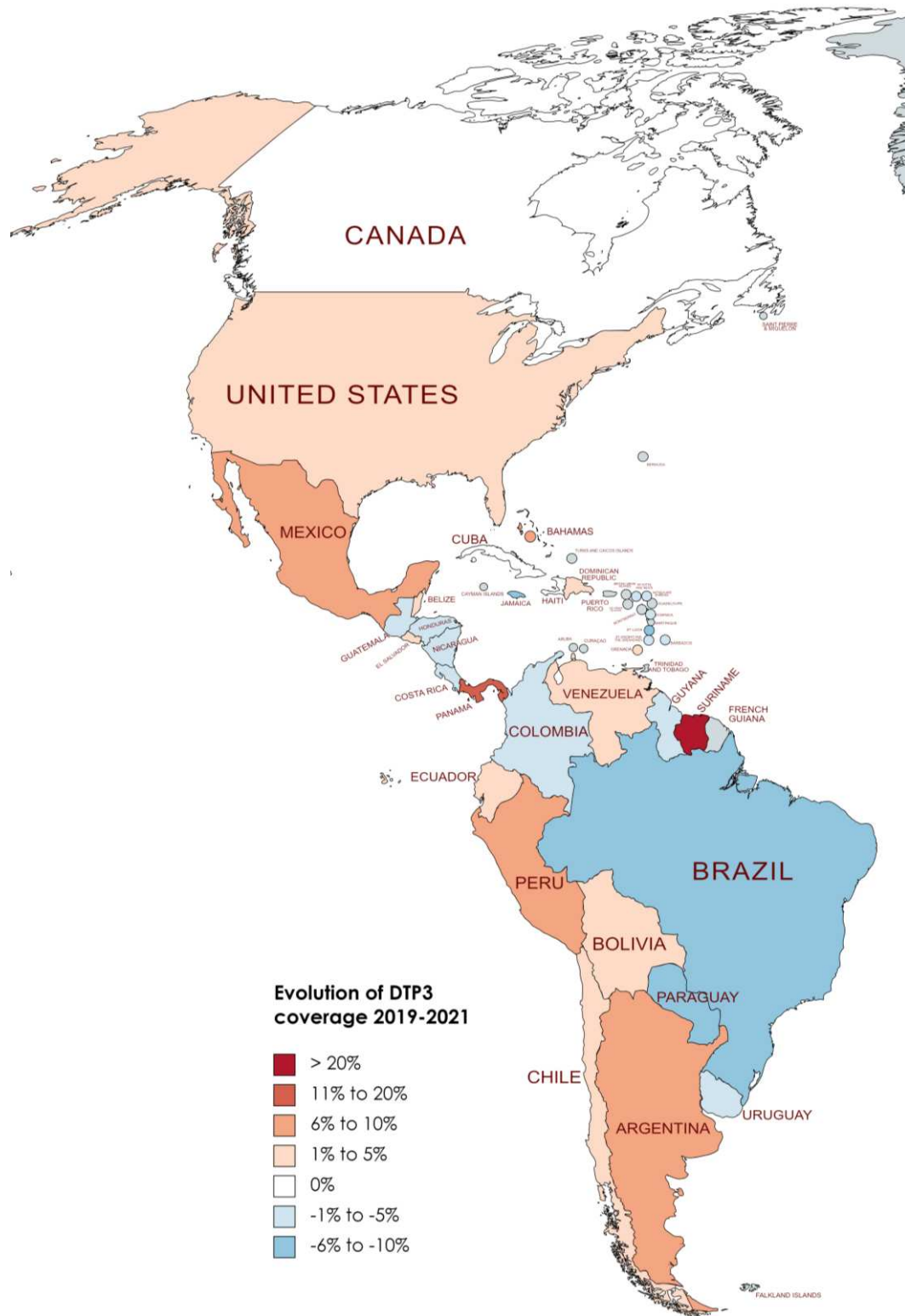


Figure 9. Absolute Changes in DTP Vaccination Coverage (%) Across American Countries between 2019 and 2021.

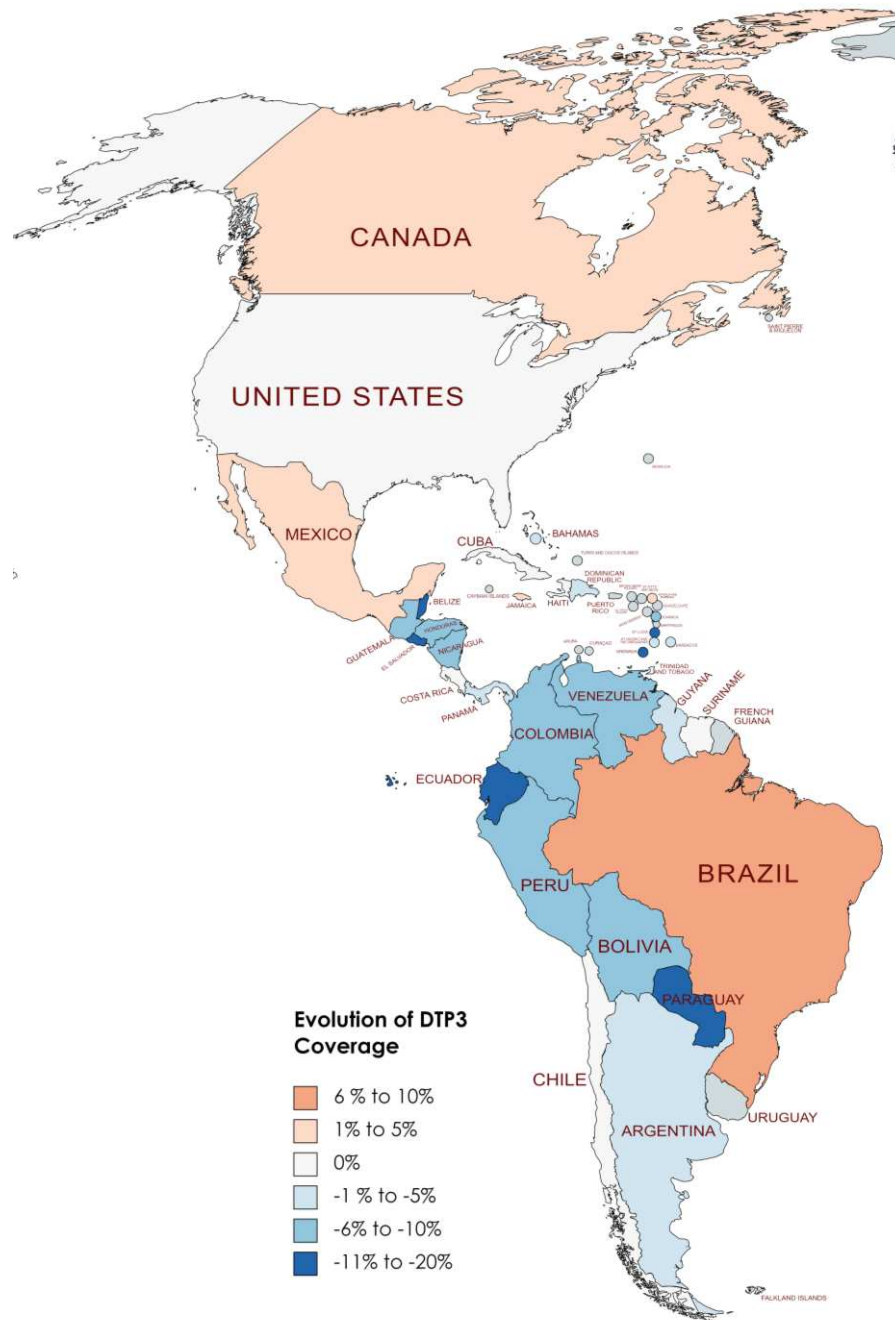


Figure 10. Absolute Changes in DTP3 Vaccination Coverage (%) Across American Countries between 2019 and 2022.

In North America, in two countries, Canada and Mexico, the DTP3 vaccine coverage slightly increased by 1% between 2019 and 2022, while in the United States, it remained the same. In South America, Brazil increased the coverage by 7%, and three countries, Chile, Suriname, and Uruguay, remained at the same level. In the other countries, the coverage decreased. In Central America, except for Costa Rica, whose rate remained equal, all the countries fell their coverage. The same happened in the Caribbean. All the countries decreased; the only exceptions were Antigua, Barbuda, and Jamaica, which increased 4% and 2%, respectively, and Cuba, Haiti, and Trinidad and Tobago, which remained at the same level. (Figure 10)

By 2019, 14 American countries (Antigua and Barbuda, Barbados, Belize, Canada, Chile, Colombia, Costa Rica, Cuba, Dominica, El Salvador, Grenada, Guyana, Jamaica, Nicaragua, Saint Lucia, Saint Kitts and Nevis, Saint Vincent and the Grenadines, Trinidad and Tobago, United States and Uruguay) had reached the WHO target of 90% coverage for the third dose of DTP by 2030.

Following the pandemic, by 2022, six countries (Barbados, Belize, Colombia, El Salvador, Grenada, Saint Lucia) dropped out of the countries that achieved the 90% DTP coverage target in 2022 compared to the 2019 list. (Figures 11 and 12)



Figure 11. American Countries Meeting the WHO 90% DTP3 Vaccination Coverage Target in 2019.



Figure 12. American Countries Meeting the WHO 90% DTP3 Vaccination Coverage Target in 2022.

Twenty countries had a JoinPoint close to 2019 (Table 5, Figures 13–32). In five countries: Antigua and Barbuda, Costa Rica, Haiti, Peru, Saint Vincent and the Grenadines, there was a JoinPoint in 2017 (95% I.C. 2014-2020). In five countries: Canada, Ecuador, Grenada, Jamaica, Nicaragua, and Paraguay, the JoinPoint was in 2018 (95% I.C. 2016-2019). In three countries, Belize, Colombia, and Saint Lucia, there was a JoinPoint in 2019 (95% I.C. 2017-2020). Finally, there were six countries: Bahamas, Dominica, Mexico, Saint Kitts and Nevis, Suriname, and Uruguay, with a JoinPoint in 2020 (95% I.C. 2014-2020). In all these countries, there was a decrease in the APC. The only exceptions were four countries, Canada, Bahamas, Mexico, and Suriname, which managed to have an increase in the period after the JoinPoint.

Table 5. Joinpoint analysis DTP3 dose coverage in America, 2012–2022.

Country	Years	APC	95% LCI	95% UCI	P
<i>Antigua and Barbuda</i>					
Total Period	2012-2022	-0.4	-0.9	0	0.04
Period 1	2012-2017	-1.2	-2.7	0.4	0.118
Period 2	2017-2022	0.3	-1.3	1.9	0.677
<i>Bahamas</i>					
Total Period	2012-2022	-1.5	-2	-0.9	< 0.001
Period 1	2012-2020	-1.8	-2.2	-1.4	< 0.001
Period 2	2020-2022	0.6	-2.7	3.9	0.697
<i>Belize</i>					
Total Period	2012-2022	-1.6	-2.6	-0.6	0.005
Period 1	2012-2019	-0.8	-1.7	0.2	0.09
Period 2	2019-2022	-4.4	-8.3	-0.3	0.04
<i>Canada</i>					
Total Period	2012-2022	0.1	0.1	0.2	0.003
Period 1	2012-2018	0	-0.1	0.1	0.931
Period 2	2018-2022	0.3	0.1	0.6	0.008
<i>Colombia</i>					
Total Period	2012-2022	-0.4	-0.9	0.1	0.102
Period 1	2012-2019	0.3	0	0.6	0.071
Period 2	2019-2022	-2.6	-3.8	-1.4	0.002
<i>Costa Rica</i>					
Total Period	2012-2022	-0.4	-0.9	0.1	0.102
Period 1	2012-2017	0.8	-0.6	2.3	0.198
Period 2	2017-2022	-0.2	-1.6	1.2	0.702
<i>Dominica</i>					
Total Period	2012-2022	-0.4	-1	0.1	0.101
Period 1	2012-2020	-0.2	-1.3	0.9	0.677
Period 2	2020-2022	-2.2	-12.5	9.3	0.635
<i>Ecuador</i>					
Total Period	2012-2022	-1.9	-3.2	-0.7	0.007
Period 1	2012-2018	-0.3	-3.2	2.8	0.843
Period 2	2018-2022	-4.8	-10.1	0.8	0.078
<i>Grenada</i>					
Total Period	2012-2022	-2.7	-4.1	-1.3	0.002
Period 1	2012-2018	-0.5	-3.5	2.6	0.71
Period 2	2018-2022	-6.5	-12.1	-0.6	0.036
<i>Haiti</i>					
Total Period	2012-2022	-3.0	-4.3	-1.7	0.001
Period 1	2012-2017	-0.8	-5.2	3.7	0.663
Period 2	2017-2022	-5.1	-9.3	-0.7	0.029
<i>Jamaica</i>					
Total Period	2012-2022	0.2	-0.3	0.7	0.476
Period 1	2012-2018	0.4	-0.8	1.6	0.427
Period 2	2018-2022	-0.7	-6	4.8	0.756
<i>Mexico</i>					
Total Period	2012-2022	-1.7	-3.1	-0.2	0.027
Period 1	2012-2020	-2.3	-4.5	0	0.048
Period 2	2020-2022	2.4	-16.3	25.2	0.783
<i>Nicaragua</i>					
Total Period	2012-2022	-0.9	-1.5	-0.4	0.006

Period 1	2012-2018	0.1	-1	1.2	0.875
Period 2	2018-2022	-2.7	-4.9	-0.6	0.022
<i>Paraguay</i>					
Total Period	2012-2022	-2.8	-4.1	-1.5	0.001
Period 1	2012-2018	-0.3	-1.1	0.6	0.506
Period 2	2018-2022	-7.2	-8.8	-5.6	< 0.001
<i>Peru</i>					
Total Period	2012-2022	-1.5	-2.6	-0.4	0.012
Period 1	2012-2017	-0.8	-5.4	4.1	0.709
Period 2	2017-2022	-2.3	-6.8	2.5	0.284
<i>Saint Kitts and Nevis</i>					
Total Period	2012-2022	0	-0.3	0.2	0.87
Period 1	2012-2020	0.1	-0.3	0.6	0.489
Period 2	2020-2022	-1.2	-7.1	5.2	0.661
<i>Saint Lucia</i>					
Total Period	2012-2022	-2.2	-3.2	-1.1	0.001
Period 1	2012-2019	-1.7	-4.1	0.8	0.141
Period 2	2019-2022	-3.8	-13.2	6.7	0.4
<i>Saint Vincent and the Grenadines</i>					
Total Period	2012-2022	-0.5	-0.9	0	0.045
Period 1	2012-2017	0.6	-0.2	1.5	0.105
Period 2	2017-2022	-1.6	-2.4	-0.8	0.003
<i>Suriname</i>					
Total Period	2012-2022	-1	-3.3	1.4	0.361
Period 1	2012-2020	-2.1	-4	-0.2	0.038
Period 2	2020-2022	7.3	-14	33.9	0.466
<i>Uruguay</i>					
Total Period	2012-2022	-0.3	-0.6	-0.1	0.016
Period 1	2012-2020	-0.4	-0.9	0	0.049
Period 2	2020-2022	0.5	-4.5	5.8	0.817

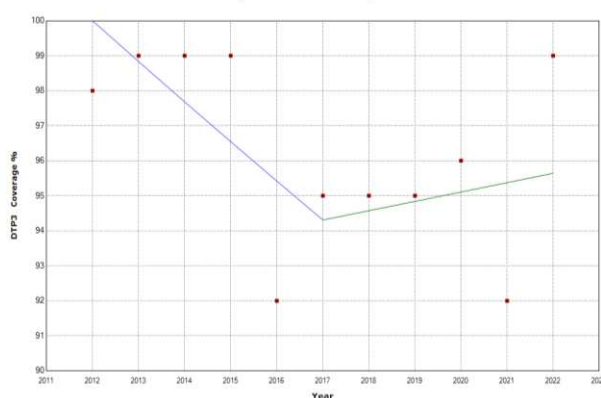


Figure 13. Third DTP dose coverage (2012-20) indicating joinpoints in Antigua and Barbuda.

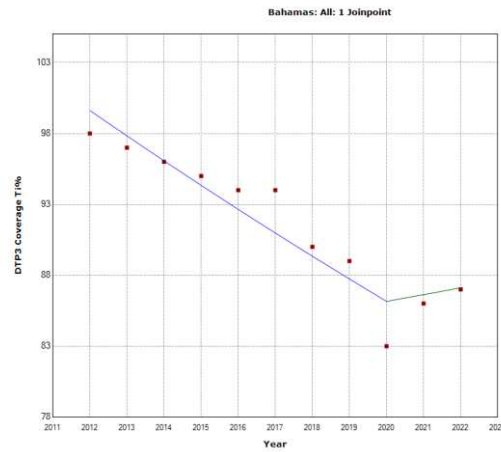


Figure 14. Third DTP dose coverage (2012-20) indicating joinpoints in the Bahamas.

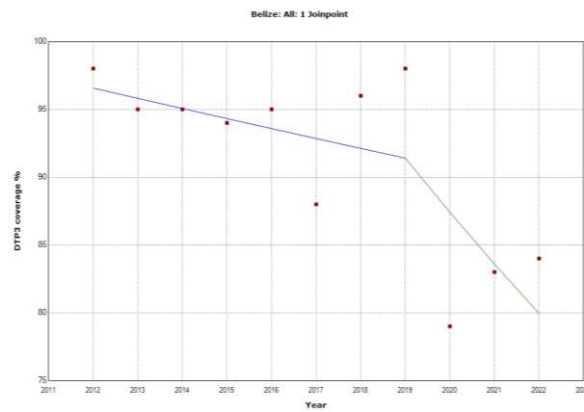


Figure 15. Third DTP dose coverage (2012-20) indicating joinpoints in Belize.

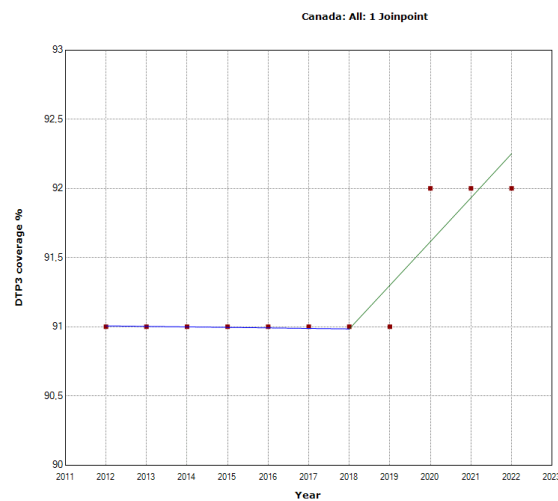


Figure 16. Third, DTP dose coverage (2012-20) indicates joinpoints in Canada.

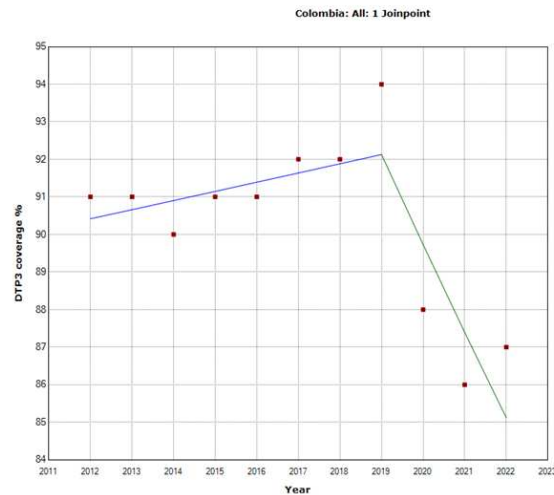


Figure 17. Third DTP dose coverage (2012-20) indicating joinpoints in Colombia.

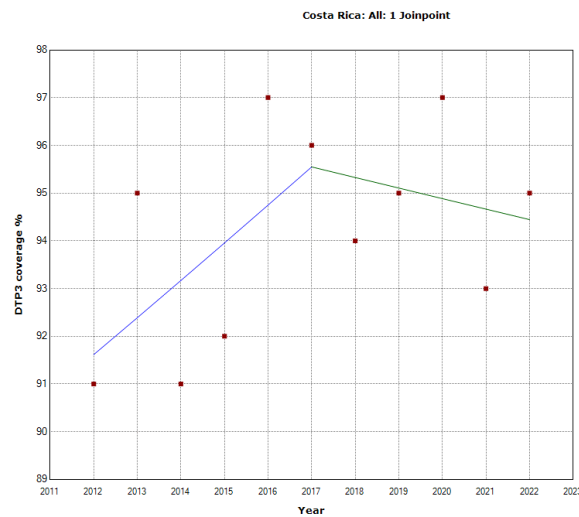


Figure 18. Third DTP dose coverage (2012-20) indicating joinpoints in Costa Rica.

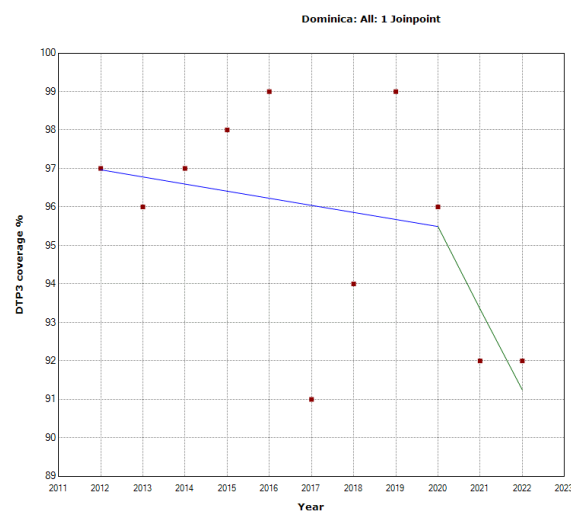


Figure 19. Third DTP dose coverage (2012-20) indicating joinpoints, Dominica.

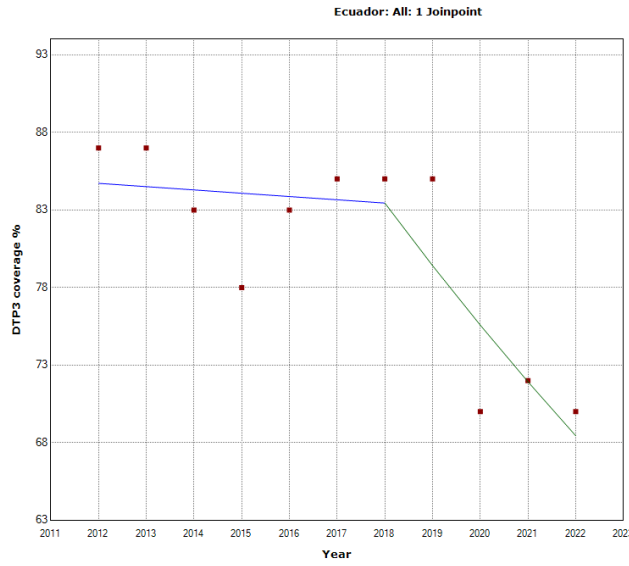


Figure 20. Third DTP dose coverage (2012-20) indicating joinpoints in Ecuador.

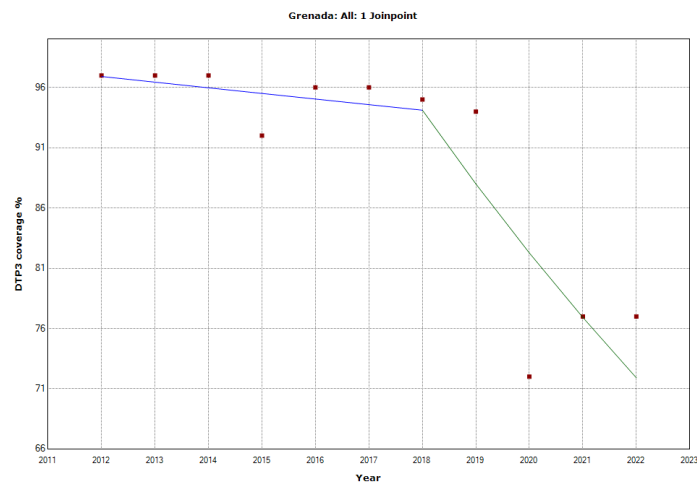


Figure 21. Third DTP dose coverage (2012-20) indicating joinpoints in Grenada.

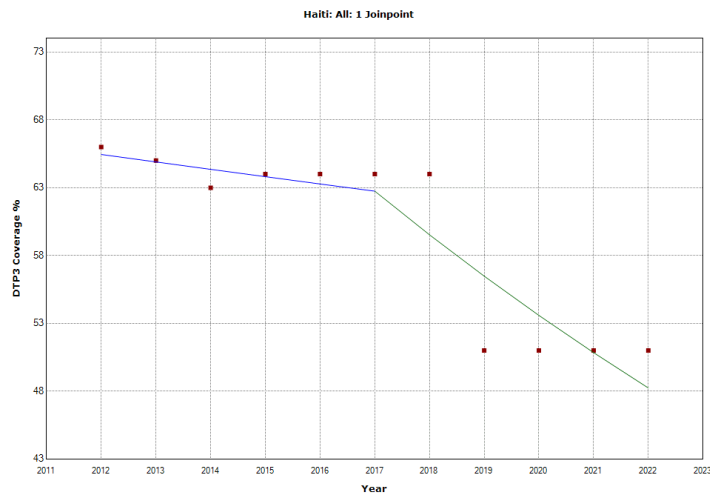


Figure 22. Third DTP dose coverage (2012-20) indicating joinpoints in Haiti.

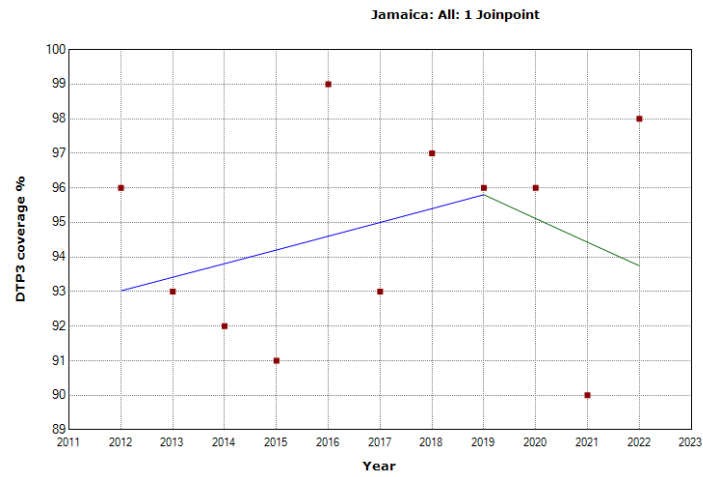


Figure 23. Third DTP dose coverage (2012-20) indicating joinpoints in Jamaica.

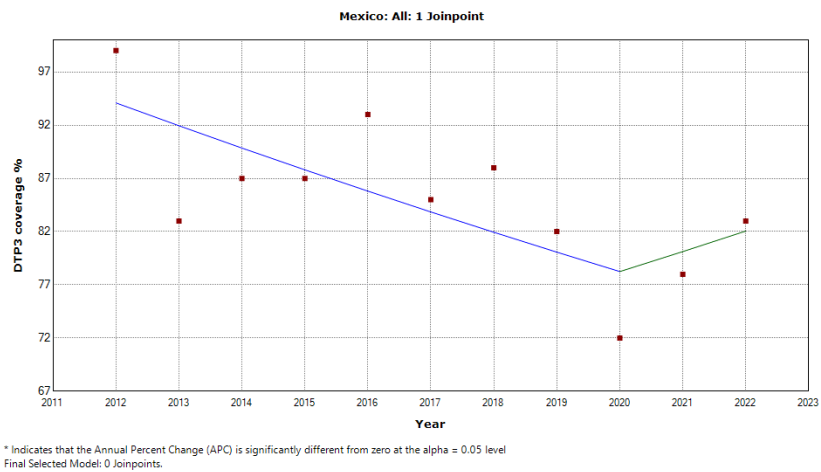


Figure 24. Third DTP dose coverage (2012-20) indicating joinpoints in Mexico.

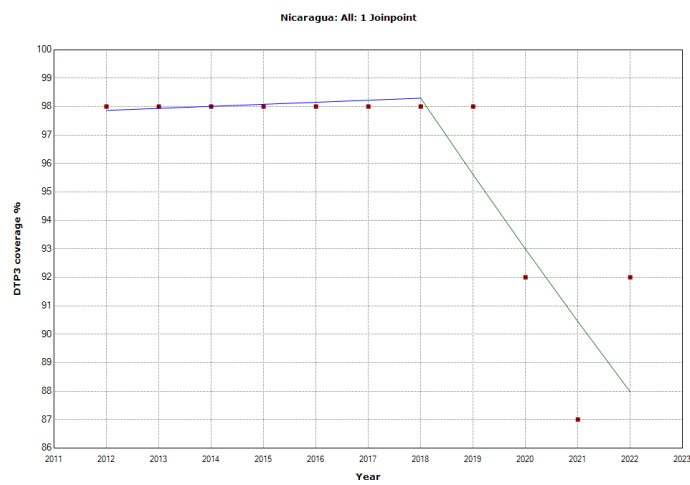


Figure 25. Third DTP dose coverage (2012-20) indicating joinpoints in Nicaragua.

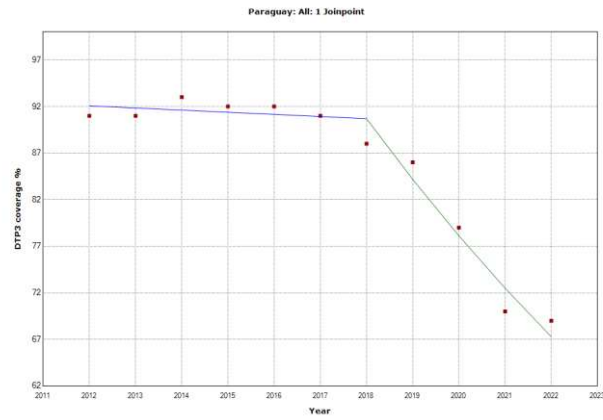


Figure 26. Third DTP dose coverage (2012-20) indicating joinpoints in Paraguay.

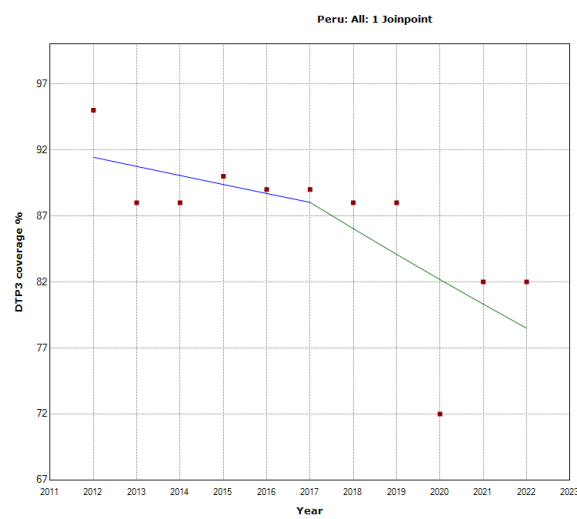


Figure 27. Third DTP dose coverage (2012-20) indicating joinpoints in Peru.

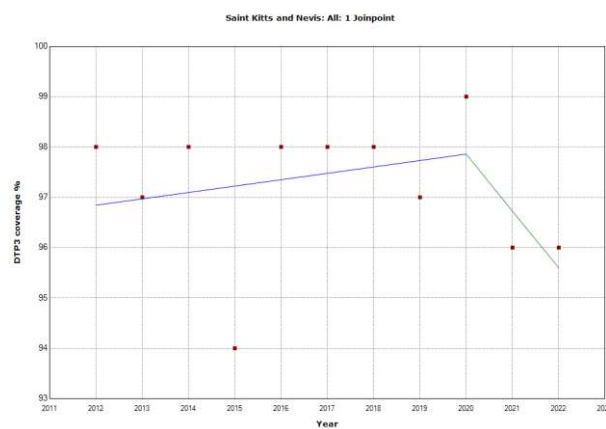


Figure 28. Third DTP dose coverage (2012-20) indicating joinpoints in Saint Kitts and Nevis.

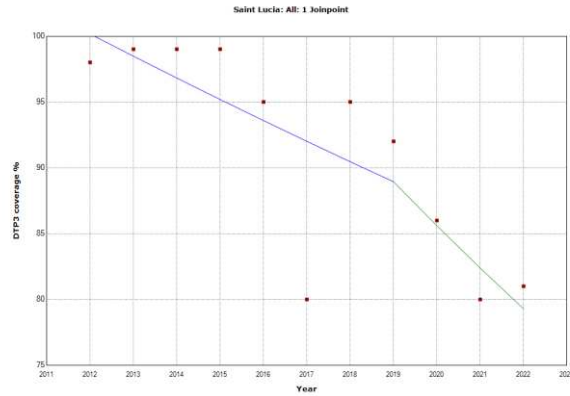


Figure 29. Third DTP dose coverage (2012-20) indicating joinpoints in Saint Lucia.

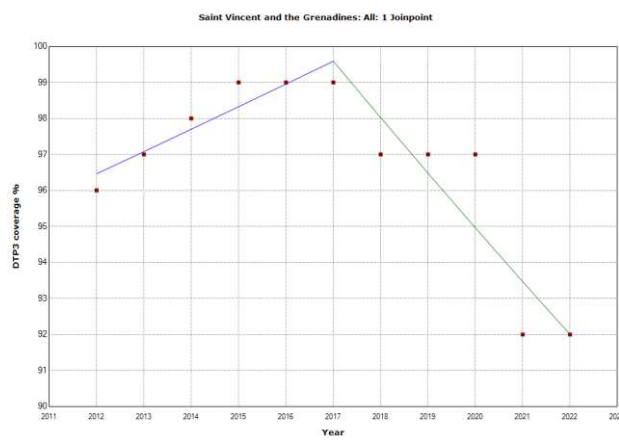


Figure 30. Third DTP dose coverage (2012-20) indicating joinpoints in Saint Vincent and the Grenadines

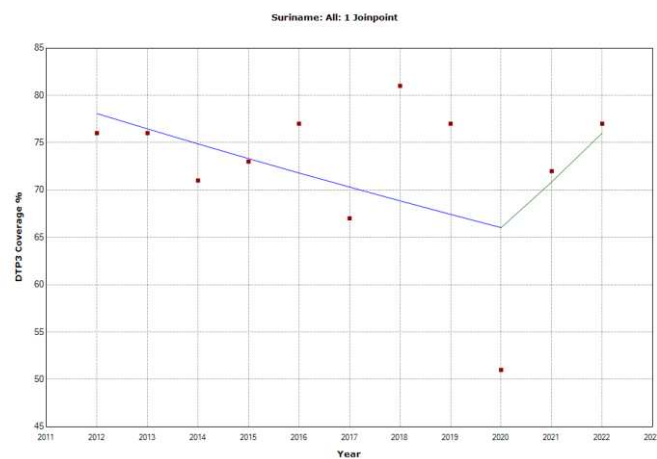


Figure 31. Third DTP dose coverage (2012-20) indicating joinpoints in Suriname.



Figure 32. Third DTP dose coverage (2012-20) indicating joinpoints in Uruguay.

Using interrupted time series analysis, we detected changes, although not significant, in all the regions of America. Table 6 presents the segmented regression analysis of DTP3 vaccine coverage parameters. (Figures 33–36)

Table 6. Segmented Regression Analysis of Regional DTP3 Vaccine Coverage.

Region	Intercept	Year	Covid-19	Interaction
<i>The Americas</i>	14,257,167.	-271,700 ***	-3,824,000 †	339,600†
<i>North America</i>	6,419,470	-77,900***	-960,900	92,490,
<i>Latin America and the Caribbean</i>	10,258,998.	-239,700	-3,408,000†	296,800
<i>Central America</i>	842,631	-9,958*	-73,740	1,035
<i>The Caribbean</i>	595,044	-5,629*	-94,750	6,845
<i>South America</i>	6,552,726	-161,900**	-2,071,000,	181,600,

† p < 0.10 *p < 0.05 **p < 0.01 *** p < 0.001.

In the Americas (Figure 33), the year's coefficient was -271,700 ($p = 0.002$), suggesting a decreasing trend in DTP3 vaccinations over the years. The COVID-19 coefficient is negative, approximately -3,824,000, indicating a decrease during the pandemic, but it is not statistically significant, with a p-value of 0.082.

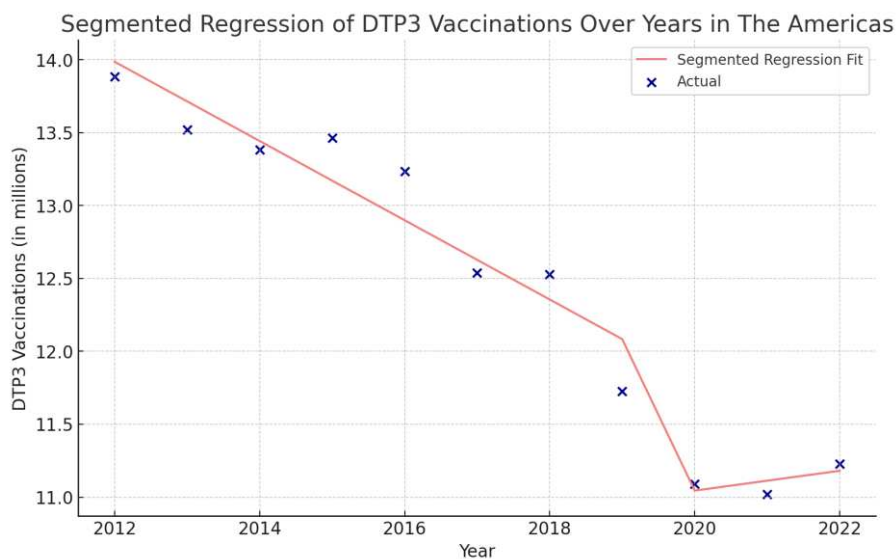


Figure 33. Segmented Regression Analysis of DTP3 in the Americas, representing the actual DTP3 vaccination numbers (in dark blue) against the predicted values from the segmented regression (in light coral).

In North America, the COVID-19 coefficient is negative, approximately -960,900, but it is not statistically significant, with a p-value of 0.140. (Figure 34)

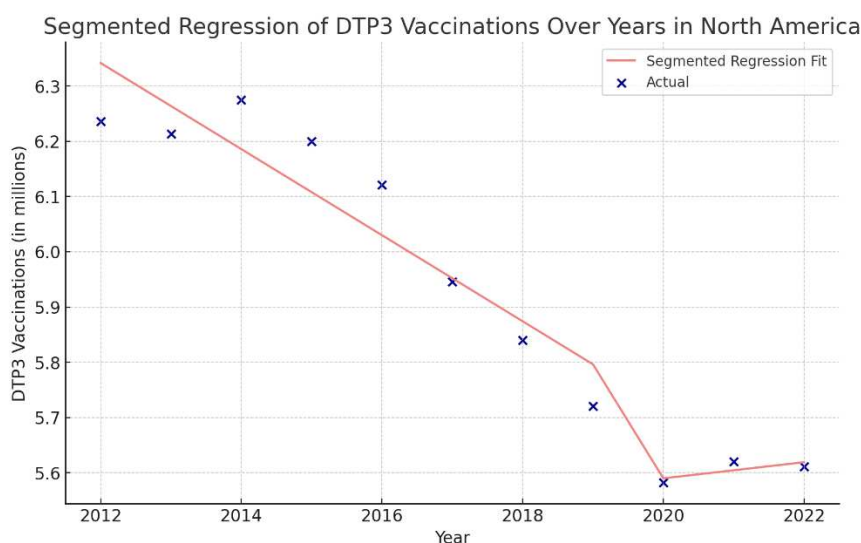


Figure 34. Segmented Regression Analysis of DTP3 in North America, representing the actual DTP3 vaccination numbers (in dark blue) against the predicted values from the segmented regression (in light coral)

In Latin America and the Caribbean, the coefficient of COVID-19 was -3,408,000, indicating a decrease during the pandemic. (Figure 35) However, the p-value for this coefficient was 0.078, which is marginally above the typical significance level of 0.05.

Segmented Regression of DTP3 Vaccinations Over Years in Latin America and the Caribbean

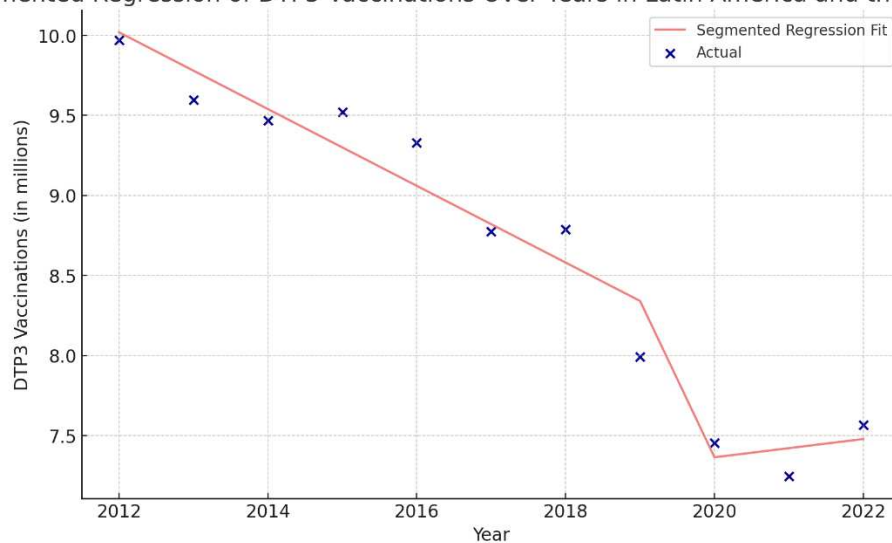


Figure 35. Segmented Regression Analysis of DTP3 Vaccination in Latin America and the Caribbean. The actual DTP3 vaccination numbers (in dark blue) against the predicted values from the segmented regression (in light coral).

In Central America, the coefficient of COVID-19 was $-73,740$, but it was not statistically significant. (Figure 36)

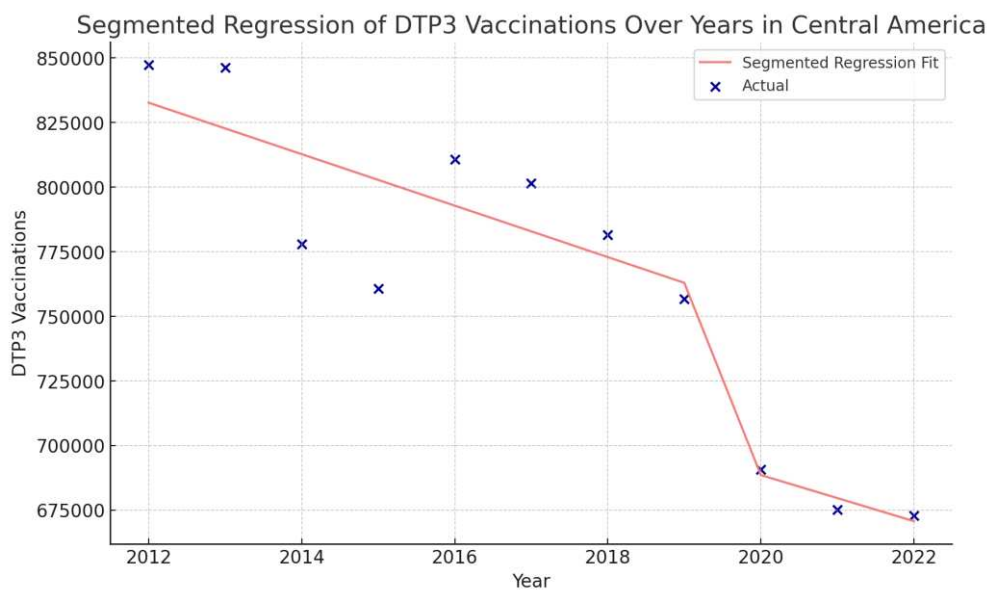


Figure 36. Segmented Regression Analysis of DTP3 vaccination in Central America. The actual DTP3 (in dark blue) against the predicted values from the segmented regression (in light coral).

In the Caribbean, the COVID-19 coefficient was negative, $-94,750$, but it was not statistically significant, with a p-value of 0.195. (Figure 37)

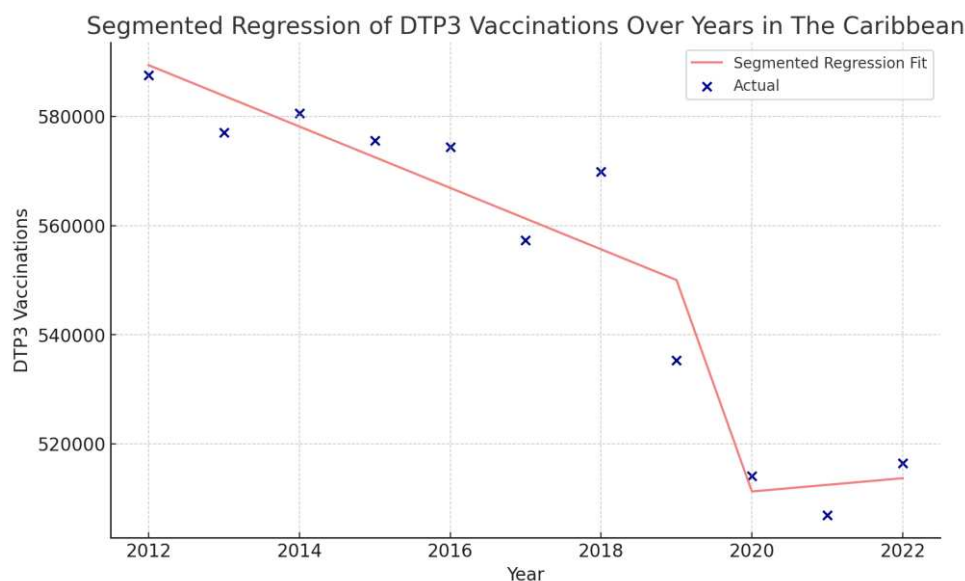


Figure 37. Segmented Regression Analysis of DTP3 Vaccination in the Caribbean. The actual DTP3 (in dark blue) against the predicted values from the segmented regression (in light coral).

In the Caribbean, the COVID-19 coefficient was negative, $-2,071,000$, but it was not statistically significant (Figure 38).

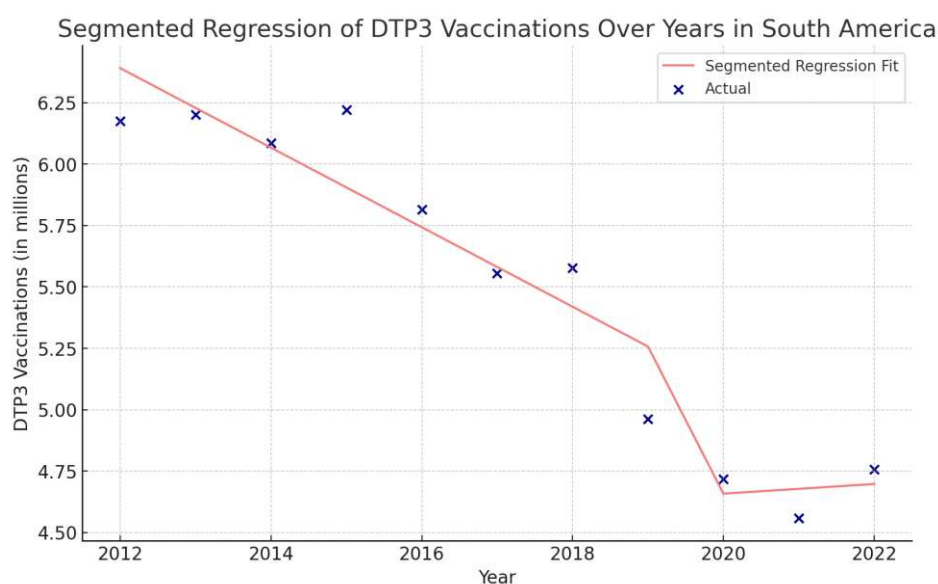


Figure 38. Segmented Regression Analysis of DTP3 Vaccination in South America. The actual DTP3 numbers (in dark blue) are represented against the predicted values from the segmented regression (in light coral).

In the segmented regression, we also detected four American countries, Belize, Grenada, Peru, and Suriname, which significantly decreased the number of children vaccinated with DTP3 after the COVID-19 pandemic. (Table 7). The United States and Mexico experienced a negative decrease close to significance. 18 American countries such as Antigua and Barbuda, Argentina, Bahamas, Barbados, Bolivia, Brazil, Canada, Chile, Dominican Republic, Ecuador, El Salvador, Haiti, Honduras, Jamaica, Nicaragua, Panama, Saint Vincent and the Grenadines, Uruguay, Venezuela also experienced a decrease in the number of children vaccinated with DTP3. However, this decrease was not statistically significant.

Table 7. Segmented Regression of the number of DTP3 vaccinations in American nations.

Nation	Intercept	Year	Covid-19	Interaction
Antigua and Barbuda	1,166	-25*	-242	41
Argentina	747,939	-21,550*	-440,868	40,473
Bahamas	5,272	-147*	-2,177	235
Barbados	2,906	-8	-444	19
Belize	73,689	-7	-3,833*	240
Bolivia	246,668	-4,856†	-80,433	6,430
Brazil	3,086,377	-101,299*	-799,678	76,649
Canada	346,374	-1,670	-28,913	4,283*
Chile	223,231	-1,354	-54,775	6,213
Colombia	671,882	277	43,507	-8,393
Costa Rica	68482	-580†	4,127	-856
Cuba	128,843	-2,206*	1,376	-726
Dominica	889	1	160	-16
Dominican Republic	183,881	170	-58,735	4,679
Ecuador	273,474	-3,456	-59,827	3,220
El Salvador	116,148	-2,777*	-27167	1,609
Grenada	2,040	-12†	-838*	42
Guatemala	366,586	-4,476	36,154	-5,709
Guyana	15,500	49	2,205	-220
Haiti	183,283	-3,133	-39,333	2,490
Honduras	215,078	-3,019	-29,014	1,396
Jamaica	39,982	-942*	-8,835	955
Mexico	2,170,515	-63,127*	-1,379,021†	131,627
Nicaragua	140,894	-108	-4,172	-885
Panama	62938	493	-48,279	4,392
Paraguay	123,679	129	48,857	-7,328
Peru	546,498	-5,221	-372,338*	34,451*
Saint Kitts and Nevis	672	-10*	123	-14
Saint Lucia	2,207	-38†	242	-37
Saint Vincent and the Grenadines	1,843	-57*	-25	1
Suriname	8105	31	-15,211*	1,421*
Trinidad and Tobago	19,470	-221*	3238	-372
United States	3,884,049	-44,760*	-1,093,444†	107,962†
Uruguay	49,522	-1,632*	-21,125	2,086
Venezuela	549,286	-26,220	-268,317	23,130

† p < 0.10 *p < 0.05 **p < 0.01.

The segmented regression model explains a high proportion of the variance in the number of children who received DTP3 doses in Belize (Figure 39), with an R2 value of 0.937, suggesting a good fit. The COVID-19 variable is significant ($p < 0.05$), with a coefficient of approximately -3,833. This suggests that the COVID-19 pandemic is associated with a decrease in the number of DTP3 vaccinations. The Interaction term has a positive coefficient of approximately 240, but this is not statistically significant.

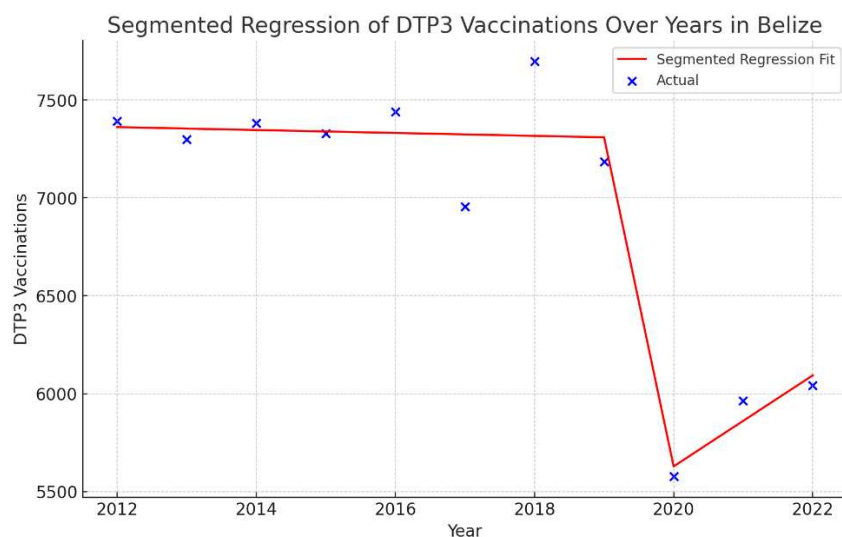


Figure 39. Segmented Regression Analysis of DTP3 Vaccination in Belize, representing the actual number of DTP3 vaccinations (in blue) and the fitted values from the segmented regression (in red).

For the data from Grenada (Figure 40), the segmented regression analysis has been conducted, yielding the following results: The R2 value of the model is 0.983, indicating that the model explains a remarkably high portion of the variance in the DTP3 vaccination numbers, suggesting a perfect fit. The coefficient for the COVID-19 variable is statistically significant ($p < 0.05$) with a value of approximately -837.68, indicating that the start of the COVID-19 pandemic is associated with a significant decrease in the number of DTP3 vaccinations. The Year variable has a negative coefficient of -12.09 and is approaching statistical significance ($p = 0.067$). This suggests a decrease in vaccinations over the years, but this trend is not statistically significant at 0.05. The Interaction term, which represents the interaction between the year and the occurrence of COVID-19, has a positive coefficient of 41.60, but this is not statistically significant ($p > 0.05$). This suggests that the interaction effect does not contribute significantly to the model.

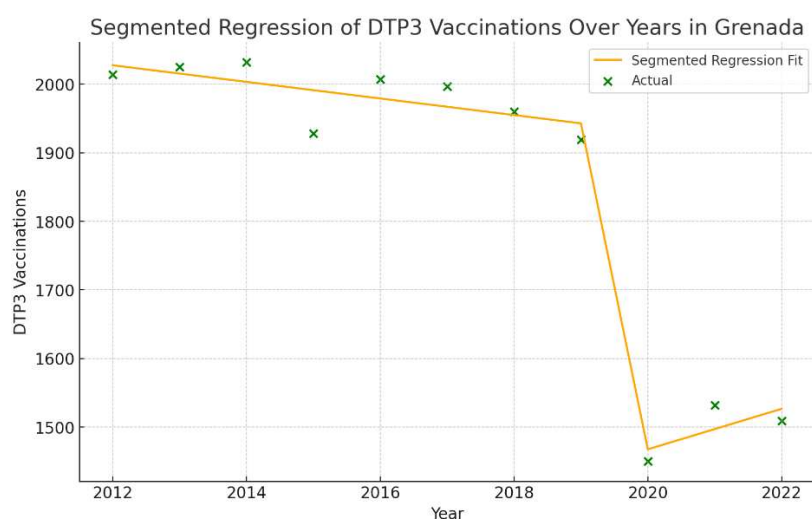


Figure 40. Segmented Regression Analysis of DTP3 vaccinations in Grenada represents the number of DTP3 vaccinations (in green) and the fitted values from the segmented regression (in orange).

The model for Peru (Figure 41) has an R2 value of 0.803, which is considered a good fit, meaning that the model explains a considerable proportion of the variance in the DTP3 vaccination numbers. The coefficient for COVID-19 is significantly negative ($p < 0.05$) with a value of approximately -372,300, indicating that the onset of the COVID-19 pandemic is associated with a substantial decrease

in the number of DTP3 vaccinations. The Interaction term is significant ($p < 0.05$) with a coefficient of approximately 34,450, indicating that the interaction between the year and the occurrence of COVID-19 has a statistically significant effect on the number of vaccinations.

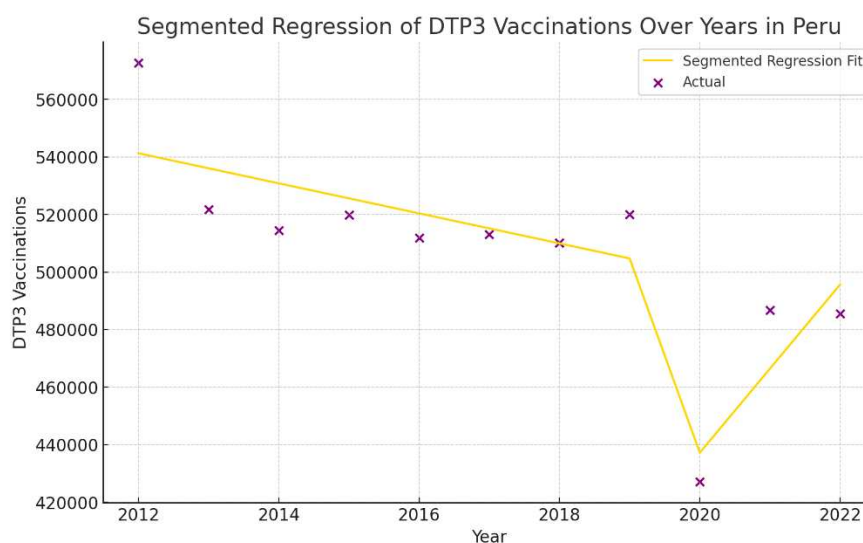


Figure 41. Segmented Regression Analysis of DTP3 vaccinations in Peru representing the actual DTP3 vaccination numbers (in purple) and the fitted values from the segmented regression (in gold).

In the segmented regression analysis for Suriname (Figure 42), the model's R^2 value is 0.733, indicating that it explains a good portion of the variance in the DTP3 vaccination numbers. The coefficient for COVID-19 is significantly negative ($p < 0.05$) with a value of approximately -15,210, which implies that the onset of the COVID-19 pandemic is associated with a significant decrease in the number of DTP3 vaccinations. The Interaction term is significant ($p < 0.05$) with a coefficient of approximately 1420, indicating that the interaction between the year and the occurrence of COVID-19 has a statistically significant effect on the number of vaccinations.

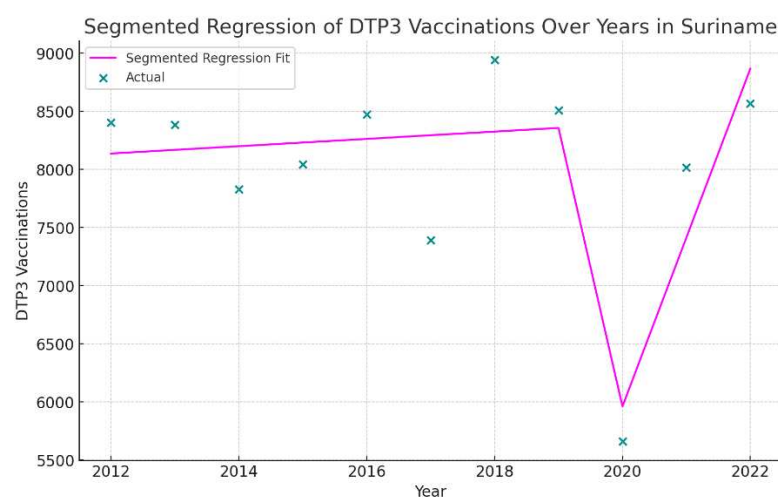


Figure 42. Segmented Regression Analysis of DTP3 vaccinations in Suriname representing the actual DTP3 vaccination numbers (in dark cyan) and the fitted values from the segmented regression (in magenta).

In Mexico (Figure 43), the model has a good fit with an R^2 value of 0.884, suggesting a perfect fit. The coefficient for Year is significantly negative ($p < 0.05$) with a value of approximately -63,130, indicating a significant decline in DTP3 vaccinations over the years. The COVID-19 coefficient is

negative with a value of approximately -1,379,000. Although this suggests a substantial decrease in vaccinations during the pandemic, it is not statistically significant ($p = 0.098$).

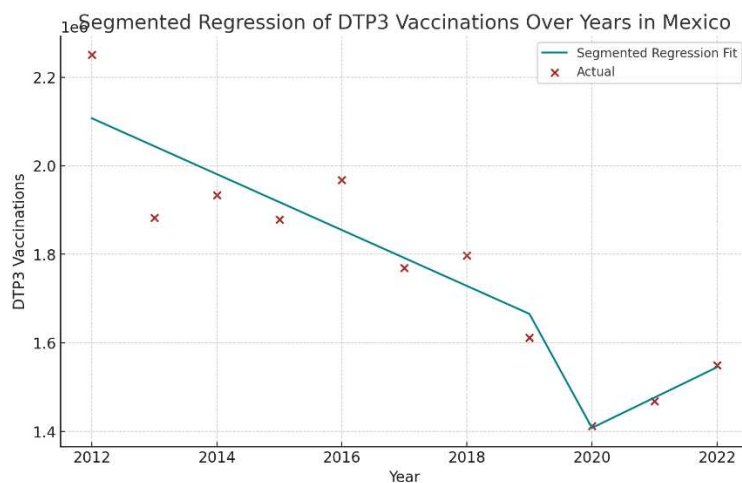


Figure 43. Segmented Regression Analysis of DTP3 vaccinations in Mexico representing the actual DTP3 vaccination numbers in (in brown) and the predicted values from the segmented regression (in teal)

The segmented regression analysis for the United States data (Figure 44) provides the following insights: the model has a good fit with an R^2 value of 0.848. The coefficient for Year is significantly negative ($p < 0.01$) with a value of approximately -44,760, suggesting a declining trend in the number of DTP3 vaccinations over the years. The COVID-19 coefficient is negative with a value of approximately -1,093,000, which would indicate a substantial decrease in the number of vaccinations during the pandemic, but it is not statistically significant ($p = 0.092$). The Interaction term has a positive coefficient of approximately 108,000, indicating a potential interaction effect between the year and the occurrence of COVID-19 on the number of vaccinations, but it is also not statistically significant ($p = 0.099$).

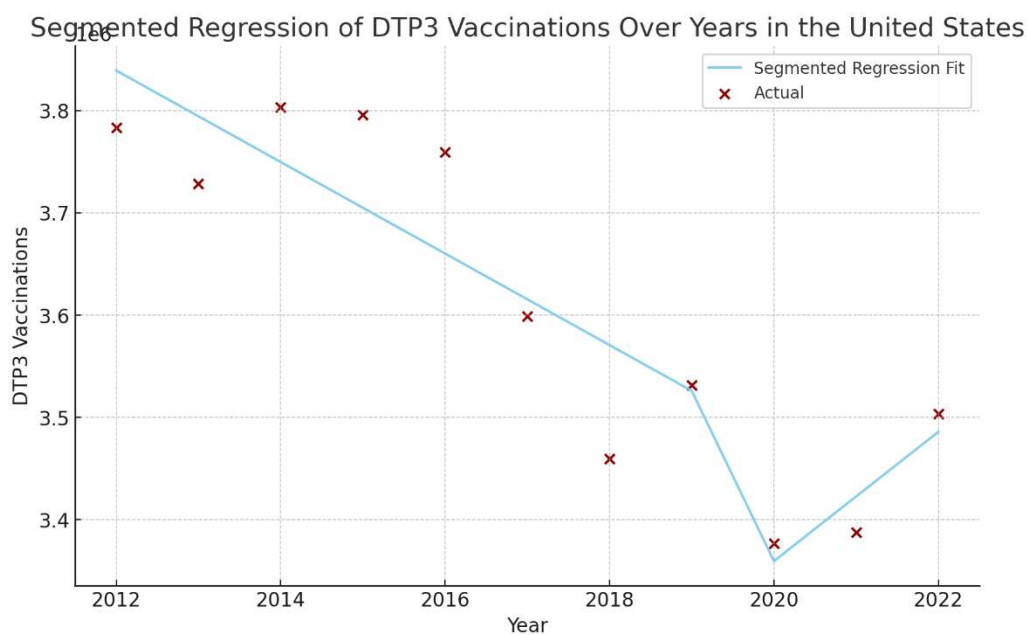


Figure 44. Segmented Regression Analysis of DTP3 vaccinations in the United States representing the actual DTP3 vaccination numbers in (in dark red) against the predicted values from the segmented regression (in sky blue).

4. Discussion

Our study aimed to analyze the impact of the COVID-19 pandemic on DTP vaccination trends in America. The results indicate that the pandemic has adversely affected vaccination coverage in several American countries, especially Central America.

4.1. Overview of the Study and Its Context

4.1.1. Methodological Considerations and Data Limitations

Our methodologies included comparing country-specific vaccination coverage between 2019 and 2022 and analyzing trends using joint points and segmented regression, which makes our findings more robust.

While acknowledging the constraints of available data and potential inconsistencies in reporting, the significance of UNICEF's dataset for this investigation remains paramount. Despite UNICEF's consistent methodology in data collection and reporting, variations in national healthcare infrastructures and reporting systems might lead to discrepancies in data quality and precision, potentially influencing the interpretations of our analysis. Furthermore, the data's compilation at national and regional scales could mask local nuances in vaccination trends, especially in areas with healthcare accessibility issues or socioeconomic disparities. Nevertheless, in the last 20 years, global immunization coverage data quality improved[68]. As of the latest data update, 2022, our study does not include real-time data from 2023 onwards. Thus, our findings might not fully capture the ongoing impact of the COVID-19 pandemic on DTP vaccination rates in the Americas. Future research, with access to more current data, would be essential in providing a more comprehensive understanding of these trends.

4.1.2. Discrepancies in Vaccine Coverage Data and Trend Analysis.

There may be inconsistencies between the number of American countries that experienced a significant decline in vaccination coverage between 2019 and 2022, 22 countries, and those in which a decreasing change in trend was detected that is smaller, only sixteen of those twenty-two countries. This discrepancy is explained because although there has been a decrease in vaccination coverage rates in some countries in the number of years of follow-up, it is not yet of the magnitude to detect a trend change in some countries.

4.2. Analysis of DTP3 Vaccination Trends

The data analysis shows a declining trend in vaccination coverage throughout the Americas, possibly due to socioeconomic and cultural factors and vaccine hesitancy, which COVID-19 exacerbated[69,70]

In the context of DTP3 vaccine coverage between 2019 and 2022, several American countries exhibited an increase in vaccine coverage. Brazil led this trend with a notable 7% increase in coverage. Following Brazil, Antigua and Barbuda saw a 4% rise, while Jamaica experienced a 2% increase. Canada and Mexico also reported modest increases of 1% each. Despite the challenging times of the COVID-19 pandemic, these enhancements in vaccine coverage highlight the effectiveness of public health interventions and the resilience of healthcare systems in these countries.

Conversely, several countries demonstrated stability in their DTP3 vaccine coverage during the same period. Countries such as Chile, Costa Rica, Cuba, Haiti, and Suriname maintained their coverage levels, with no percentage change observed. Amidst the global health crisis, this stability underscores the strength and consistency of vaccination programs in these nations. It suggests that these countries successfully navigated the complexities introduced by the pandemic, ensuring uninterrupted vaccine delivery to their populations.

However, the study also identified countries with declining DTP3 vaccine coverage. The Dominican Republic, Guyana, Panama, Saint Kitts, and Nevis experienced a 1% decrease, while Argentina faced a 2% decline. These reductions highlight the challenges and disruptions caused by

the COVID-19 pandemic, potentially reflecting resource reallocation, access issues, or public hesitancy toward vaccination. It underscores the need for focused efforts to strengthen and adapt vaccination programs in the face of such unprecedented global health challenges.

We found that DTP3 coverage remained stable during the whole pandemic period 2019-2022 across most North American countries, as depicted in Table 4. This observation warrants further exploration, as it contrasts with the 4% absolute decrease in vaccine coverage reported across America during the same period. Canada and Mexico slightly increased the coverage of DTP3 in the period between 2019 and 2022, while the United States remained with the same coverage[4]. The countries that did not have their coverage affected at the end of the pandemic period were Haiti, Chile, Costa Rica, Cuba, Suriname, Trinidad and Tobago, Uruguay, United States. These findings may reflect the effectiveness of their national immunization programs and robust healthcare systems, which allowed these countries to maintain their vaccination rates despite the various obstacles posed by the ongoing global COVID-19 pandemic. Nevertheless, there are differences in subnational units. For example, in Haiti, 80% of the subnational units experienced a 5% or higher reduction in DTP3 service volume in the third quarter of 2022[71].

Conversely, during this period, Grenada, Paraguay, Ecuador, El Salvador, Belize, Saint Lucia, Honduras, Venezuela, Colombia, Dominica, Bolivia, Guatemala, Nicaragua, Peru, Saint Vincent and the Grenadines, Barbados, Argentina, Bahamas, Dominican Republic, Guyana, Panama, Saint Kitts and Nevis experienced decreases in DTP3 vaccine coverage. Many countries had a slight decline in coverage of -1%, like the Dominican Republic, Guyana, Panama, Saint Kitts and Nevis, with no statistically significant decrease. Furthermore, other countries like Grenada and Saint Lucia had massive reductions -17% and 11%- but they were not statistically significant.

In contrast, in countries like Paraguay, Ecuador, El Salvador, Belize, and Honduras, absolute coverage decreased from -17% to -10%. This decrease may be attributed to the country's ongoing health system challenges, including vaccine supply chain inefficiencies, which could have been exacerbated by the additional strain of the COVID-19 pandemic (3).

We have demonstrated significant decreases in vaccine coverage in many American countries. We also show a change in the coverage trend in Latin America and the Caribbean. The change in the trend, accelerating the decrease in coverage, was found in all the subregions. It was statistically significant in the Caribbean ($P=0.031$) and South America ($p=0.001$). There was also an acceleration in coverage decrease in Central America, which was not yet statistically significant due to the reduced follow-up period. Our data agrees with the bibliography that shows that in Latin America and the Caribbean, the coverage of DTP3 experienced a decrease of -5,06% between 2019 and 2021. The coverage rate decreased from 79% in 2019 to 75% in 2020 [35].

A significant observation in our comprehensive study examining DTP vaccination trends in America was the reduction in DTP3 vaccine coverage from 2019-2022 in Central America. This period, coinciding with the COVID-19 pandemic, marked an acceleration in the decrease in coverage that was a notable deviation from the previous downward trend, with an APC of -2.6%, indicating a substantial decrease in vaccination rates.

4.3. Comparative Global and Regional Perspectives

The global decline in vaccine coverage, spurred by the COVID-19 pandemic, extends beyond DTP vaccines. From January to December 2020, approximately 30 million children missed DTP3 vaccinations, and 27.2 million missed MCV1 vaccinations [32]. It has been reported that there was also a reduction in HPV in some parts of the United States[69]. The worldwide coverage of DTP3 experienced a decline of 5.81% from 2019 to 2021, decreasing from 86% to 81% [48]. In considering the broader implications of our findings, it is crucial to assess the impact of the digital divide on data reporting. In regions of the Americas with limited access to technological resources, the accuracy and timeliness of data reporting may be compromised. This factor is crucial in understanding the regional disparities in vaccine coverage and the challenges in data collection.

The decrease in DTP coverage is a global problem. The Global coverage of the DTP3 decreased from 86% in 2019 to 83% in 2020 [72][48]. Similar declines had been found in Africa and Asia. [41,73].

In contrast to other regions, Europe experienced a minor reduction in vaccination coverage. Specifically, the coverage for the third dose of the Diphtheria-Tetanus-Pertussis (DTP3) vaccine saw a marginal decline of 1.05% from 2019 to 2021. This resulted in a slight dip in coverage rates, from 95% in 2019 to 94% in 2020. Furthermore, a comparative analysis with other regions, such as Africa or Europe, could offer valuable insights into global patterns and region-specific challenges in maintaining vaccination during the pandemic. Such a comparative perspective could help identify unique challenges and successful strategies in different regions, offering lessons for future healthcare planning and policy formulation.

4.4. Influential Factors and Challenges

Socioeconomic factors have been pivotal in influencing vaccine accessibility during the pandemic. Economic challenges exacerbated by the pandemic have widened existing disparities in healthcare access, further impacting vaccination rates. A detailed examination of these socioeconomic variables provides a more nuanced understanding of the vaccination landscape across different socio-demographic groups.

Several factors may explain the change in vaccine coverage. Country-level factors, such as high fertility rates, and community-level factors, such as high illiteracy rates, contribute to the prevalence of unvaccinated children[33]. Research conducted in the U.S. revealed that for all types of hepatitis vaccines, both adherence and completion rates are notably low, exhibiting considerable differences across various socio-demographic and clinical profiles. The likelihood of poor adherence and incomplete vaccination was typically linked to factors such as being male, belonging to a younger age group, identifying as Black or Hispanic, and having lower levels of education and household income[74].

In Africa, the primary factors contributing to incomplete vaccination were time limitations faced by caregivers, insufficient understanding about immunization, the absence of vaccines or personnel at healthcare facilities, missed opportunities for vaccination, concerns regarding minor side effects, limited access to vaccination services, and the vaccination beliefs held by caregivers[75]. Multiple missed vaccination opportunities exist among different populations and geographical regions. A recent meta-analysis has found that the prevalence of incomplete immunization (failing to receive any vaccination doses) in Africa was 35.5%. The main risk factors were home birth, rural residence, lack of antenatal care visits, knowledge of immunizations, and maternal illiteracy[76].

Additionally, American countries varied public health policies and COVID-19 response strategies have potentially influenced DTP vaccination rates[50]. Redirecting healthcare resources from routine vaccinations to COVID-19 response efforts in some regions may have contributed to the observed decline in vaccine coverage.

These declines underscore the profound impact of the COVID-19 pandemic on routine vaccination programs in the continent, signaling a need for focused efforts to recover and enhance vaccine coverage. Covid-19 had an impact on children's vaccination. The decrease in vaccination rates can be attributed to several factors related to the COVID-19 pandemic, such as the redirection of healthcare resources towards managing the outbreak, lockdowns, and restrictions on movement that impeded access to vaccination services. In a survey conducted to parents of children 0-4 years from Europe, America, and Australia, 83% of the parents believed it essential for their child to continue receiving recommended vaccines during the COVID-19 pandemic. Half of routine vaccine appointments were delayed or canceled due to the pandemic. Nevertheless, 61% of the parents said they would like to catch up once COVID-19 restrictions were lifted[77].

4.5 Strategies and Interventions for Enhancing Vaccine Coverage

Interestingly, despite the pandemic's difficulties, some nations, including Canada, Mexico, Jamaica, Antigua and Barbuda, and Brazil, were able to increase their vaccination coverage. It is worth noting the case of Brazil, which increased its vaccination coverage by 7% at the end of the Covid 19 pandemic. This increase may be attributed to effective immunization strategies, targeted interventions, or increased government support for vaccination programs during the crisis. It is

crucial to examine and learn from the experiences of these countries to improve immunization services in the face of future crises.

As there are many incomplete vaccinations and the parents are willing to catch up, healthcare services should try to reach the parents[4]. Strategies need to be developed to increase DTP3 vaccination coverage. One strategy that has been suggested is co-administration with other vaccines[78].

The differences among countries highlight the need for tailored strategies to improve vaccine coverage, particularly in countries with decreasing trends. Continuous monitoring of immunization programs, addressing health system barriers, and community engagement are vital for maintaining and enhancing vaccine coverage in these settings.

Our study's findings align with other research suggesting that the COVID-19 pandemic has disrupted essential health services, including vaccination programs, worldwide. Additionally, fear of contracting the virus may have led to a reluctance among parents to bring their children to healthcare facilities for vaccination. Healthcare workers, especially community nurses, have an essential role[20].

Last, policies should enhance public awareness about the importance of routine vaccinations and combating misinformation. Community-based interventions and social media campaigns can play a crucial role in increasing vaccine uptake[14,79].

4.6. The Role of Healthcare Systems and Planning

The COVID-19 pandemic's disruption has brought attention to the need for resilient health systems that can continue providing essential medical services in times of need. [80]. The significant differences in vaccination trends across regions highlight the need for tailored public health strategies. Policies must be region-specific, considering each area's unique challenges and resources.

Efforts should be made to strengthen vaccination programs and improve coverage across the continent, particularly in the regions most affected by the decrease in vaccination rates[81]. The decline in vaccination rates, especially in areas with weaker healthcare infrastructures, underscores the need to strengthen health systems, ensure adequate funding, train healthcare workers, and improve vaccine supply chains.

4.7. Looking to the Future

The implications of reduced vaccination coverage are significant, as it may lead to outbreaks of vaccine-preventable diseases, such as diphtheria, tetanus, and pertussis. These outbreaks can strain already overwhelmed healthcare systems and further exacerbate the impact of the COVID-19 pandemic on public health in America. It is essential to address the decline in vaccination rates and implement strategies to ensure the continuity of immunization services. The risks associated with suspension or vaccination have been demonstrated to outweigh the risk of contracting COVID-19 while receiving routine immunizations [82].

Addressing these factors through targeted interventions and policies is essential to improve immunization rates and ensure the health of these children. Geographical and economic factors, access to healthcare services, the grade of development of healthcare infrastructure, vaccine supply chain issues, sociocultural factors, political stability, and the Government's commitment to vaccination may modulate the impact of the COVID-19 pandemic on DTP vaccination coverage [83,84]. We can observe that the countries that dropped out of the list in 2021 of those achieving WHO's DPT objectives are spread across Latin American and Caribbean regions. The decline in the number of countries reaching the target of 90% coverage for the third dose of DTP is observed across various Latin American regions. It is essential to accurately assess the regional impact by comparing the countries that achieved the WHO target in 2019 and 2022. Another issue is that, even if vaccination programs improve and return to pre-pandemic levels, they might not do so to the extent required for catch-up immunizations, which may take a long time[85]. Because of this delay, there may be an increased chance of outbreaks of diseases that can be prevented by vaccination[86].

Efficient planning, organization, and swift implementation are crucial for expediting the vaccine distribution process and ensuring a speedy recovery of vaccine coverage[87]. Collaboration between governments, healthcare providers, and international organizations is vital to ensure that progress in achieving vaccination targets is not lost [88] and to protect the health of American populations from vaccine-preventable diseases. We should plan for the next pandemic, analyzing and replicating the strategies of countries that have successfully increased or maintained high vaccination rates post-pandemic, which could be beneficial. It is also essential to strengthen epidemiology services related to preventing vaccine-preventable diseases. Continuous monitoring and evaluation of vaccination programs are crucial. Identifying and addressing issues promptly can avoid further declines in vaccination rates.

Despite initial fears and logistical challenges like transportation restrictions, community commitment to vaccination during the pandemic remained strong in many countries. Systemic changes within healthcare, such as staff reallocations, caused temporary delays but were efficiently addressed. Notably, some community misconceptions about the pandemic existed but did not significantly deter vaccination efforts, reflecting a deep-rooted trust in the importance of vaccines[89]. It is crucial to monitor subnational units to avoid inequities.[71]

5. Conclusions

This study comprehensively assessed the impact of the COVID-19 pandemic on DTP3 vaccination coverage in the Americas from 2012 to 2022. The findings indicate a significant and concerning decline in vaccination rates, particularly after 2019. The overall annual percentage change (APC) for the entire period was -1.4%, with an absolute decrease in vaccine coverage of -4% from 2019 to 2022. Notably, the most substantial relative decrease occurred in Central America, with a 7.87% reduction in coverage. The JoinPoint analysis highlighted distinct temporal shifts in vaccination trends across various regions. In North America, the change was minimal and not statistically significant, with an APC of -0.1%.

In contrast, Latin America and the Caribbean experienced a more pronounced decline, with an APC of -2.1%. The situation in Central America and the Caribbean was similar, with APCs of -1.3% and -0.7%, respectively, indicating a downward trend in vaccination rates. South America faced the steepest decline, with an APC of -2.5%, intensifying to -3.1% in the latter part of the study period. Interestingly, while the pandemic adversely affected vaccination coverage in most countries, some nations like Brazil, Antigua and Barbuda, and Jamaica showed increased DTP3 vaccine coverage post-pandemic. Several countries, including Chile, Costa Rica, Cuba, Haiti, Suriname, Trinidad and Tobago, the United States, and Uruguay, maintained stable vaccination rates. The study's results are alarming, considering the importance of maintaining high DTP vaccination coverage to prevent outbreaks of vaccine-preventable diseases. The pandemic's disruptive impact on public health initiatives is underscored by the decline in coverage rates, particularly in countries that had previously met the WHO target of 90% coverage. This decline in vaccination rates highlights the need for renewed efforts in vaccination campaigns and public health strategies to reverse the negative trends and ensure the well-being of populations across the Americas.

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References

- Ota, M. O. C.; de Moraes, J. C.; Vojtek, I.; Constenla, D.; Doherty, T. M.; Cintra, O.; Kirigia, J. M. Unveiling the Contributions of Immunization for Progressing towards Universal Health Coverage. *Hum Vaccin Immunother* **2022**, *18* (1). <https://doi.org/10.1080/21645515.2022.2036048>.
- Suffel, A. M.; Ojo-Aromokudu, O.; Carreira, H.; Mounier-Jack, S.; Osborn, D.; Warren-Gash, C.; McDonald, H. I. Exploring the Impact of Mental Health Conditions on Vaccine Uptake in High-Income Countries: A Systematic Review. *BMC Psychiatry* **2023**, *23* (1), 15. <https://doi.org/10.1186/s12888-022-04512-y>.
- Hassan, M. N. A Survey on Hygienic Practices and Immunization Coverage among 12-59 Months Old Children in Urban Slum, Barishal, Bangladesh. *Asian Journal of Medical and Biological Research* **2022**, *8* (4), 277–285. <https://doi.org/10.3329/ajmbr.v8i4.62670>.
- Evans, A.; Mahar, A. L.; Deb, B.; Boblitz, A.; Brownell, M.; Guttman, A.; Stukel, T. A.; Cohen, E.; Sarkar, J.; Eze, N.; Katz, A.; Raveendran, T.; Saunders, N. Gaps in Childhood Immunizations and Preventive Care Visits during the COVID-19 Pandemic: A Population-Based Cohort Study of Children in Ontario and Manitoba, Canada, 2016–2021. *Canadian Journal of Public Health* **2023**, *114* (5), 774–786. <https://doi.org/10.17269/s41997-023-00797-y>.
- Stein, R. A. Vaccination: A Public Health Intervention That Changed History & Is Changing with History. *Am Biol Teach* **2011**, *73* (9), 513–519. <https://doi.org/10.1525/abt.2011.73.9.3>.
- Pan, J.; Wang, Y.; Cao, L.; Wang, Y.; Zhao, Q.; Tang, S.; Gong, W.; Guo, L.; Liu, Z.; Wen, Z.; Zheng, B.; Wang, W. Impact of Immunization Programs on 11 Childhood Vaccine-Preventable Diseases in China: 1950–2018. *The Innovation* **2021**, *2* (2), 100113. <https://doi.org/10.1016/J.XINN.2021.100113>.
- Espinal, M. A. The Pan American Health Organization: 120 Years in the Americas Hemisphere. *The Lancet Regional Health - Americas* **2023**, *21*, 100488. <https://doi.org/10.1016/j.lana.2023.100488>.
- Zulfan, G. P.; Sihombing, J. A.; Amin, D. M.; Widiyanti, A. D.; Berti, M. P. E.; Murtiani, F. Clinical Manifestation of Childhood Diphtheria. *Jurnal Ilmiah Kedokteran Wijaya Kusuma* **2023**, *12* (1), 1. <https://doi.org/10.30742/jikw.v12i1.2468>.
- WHO. Global Vaccine Action Plan 2011–2020; WHO Press: Geneva, 2013.
- Shahid, A. S. M. S. Bin; Rahman, A. E.; Shahunja, K. M.; Afroze, F.; Sarmin, M.; Nuzhat, S.; Alam, T.; Chowdhury, F.; Sultana, M. S.; Ackhter, M. M.; Parvin, I.; Saha, H.; Islam, S. Bin; Shahrin, L.; Ahmed, T.; Chisti, M. J. Vaccination Following the Expanded Programme on Immunization Schedule Could Help to Reduce Deaths in Children under Five Hospitalized for Pneumonia and Severe Pneumonia in a Developing Country. *Front Pediatr* **2023**, *11*. <https://doi.org/10.3389/fped.2023.1054335>.
- Atteraya, M. S.; Song, I. H.; Ebrahim, N. B.; Gnawali, S.; Kim, E.; Dhakal, T. Inequalities in Childhood Immunisation in South Asia. *Int J Environ Res Public Health* **2023**, *20* (3), 1755. <https://doi.org/10.3390/ijerph20031755>.
- Basu, S.; Ashok, G.; Debroy, R.; Ramaiah, S.; Livingstone, P.; Anbarasu, A. Impact of the COVID-19 Pandemic on Routine Vaccine Landscape: A Global Perspective. *Hum Vaccin Immunother* **2023**, *19* (1). <https://doi.org/10.1080/21645515.2023.2199656>.
- Budu, E.; Ahinkorah, B. O.; Guets, W.; Ameyaw, E. K.; Essuman, M. A.; Yaya, S. Socioeconomic and Residence-based Related Inequality in Childhood Vaccination in Sub-Saharan Africa: Evidence from Benin. *Health Sci Rep* **2023**, *6* (4). <https://doi.org/10.1002/hsr2.1198>.
- Albers, A. N.; Wright, E.; Thaker, J.; Conway, K.; Daley, M. F.; Newcomer, S. R. Childhood Vaccination Practices and Parental Hesitancy Barriers in Rural and Urban Primary Care Settings. *J Community Health* **2023**, *48* (5), 798–809. <https://doi.org/10.1007/s10900-023-01226-4>.
- Santoli, J. M.; Lindley, M. C.; DeSilva, M. B.; Kharbanda, E. O.; Daley, M. F.; Galloway, L.; Gee, J.; Glover, M.; Herring, B.; Kang, Y.; Lucas, P.; Noblit, C.; Tropper, J.; Vogt, T.; Weintraub, E. Effects of the COVID-19 Pandemic on Routine Pediatric Vaccine Ordering and Administration — United States, 2020. *MMWR Morb Mortal Wkly Rep* **2020**, *69* (19), 591–593. <https://doi.org/10.15585/mmwr.mm6919e2>.
- Zhong, Y.; Clapham, H. E.; Aishworiya, R.; Chua, Y. X.; Mathews, J.; Ong, M.; Wang, J.; Murugasu, B.; Chiang, W. C.; Lee, B. W.; Chin, H.-L. Childhood Vaccinations: Hidden Impact of COVID-19 on Children in Singapore. *Vaccine* **2021**, *39* (5), 780–785. <https://doi.org/10.1016/j.vaccine.2020.12.054>.
- Tolera, S. T., Kaweti, G., & Aboma, L. M. Article Review on Potential Impact of COVID-19 Pandemic on Socioeconomic of Ethiopia, Africa. *Health Sciences* **2022**, *11* (8), 19–30.
- Yang, J.; Vaghela, S.; Yarnoff, B.; De Boisvilliers, S.; Di Fusco, M.; Wiemken, T. L.; Kyaw, M. H.; McLaughlin, J. M.; Nguyen, J. L. Estimated Global Public Health and Economic Impact of COVID-19 Vaccines in the Pre-Omicron Era Using Real-World Empirical Data. *Expert Rev Vaccines* **2023**, *22* (1), 54–65. <https://doi.org/10.1080/14760584.2023.2157817>.
- Chen, X.; Huang, H.; Ju, J.; Sun, R.; Zhang, J. Impact of Vaccination on the COVID-19 Pandemic in U.S. States. *Sci Rep* **2022**, *12* (1), 1554. <https://doi.org/10.1038/s41598-022-05498-z>.
- Heffernan, C. The 'New Normal': Delivering Childhood Immunisations during the COVID-19 Pandemic. *Practice Nursing* **2020**, *31* (9).

21. Athiyaman, A.; Ajayi, T.; Mutuku, F.; Luwaga, F.; Bryer, S.; Giwa, O.; Mngemane, S.; Edwige, N. N.; Berman, L. Recovering from the Unprecedented Backsliding in Immunization Coverage: Learnings from Country Programming in Five Countries through the Past Two Years of COVID-19 Pandemic Disruptions. *Vaccines (Basel)* **2023**, *11* (2), 375. <https://doi.org/10.3390/vaccines11020375>.
22. Naor, M.; Pinto, G. D.; Davidov, P.; Abdrbo, L. Rapidly Establishing an Ultra-Cold Supply Chain of Vaccines in Israel: Evidence for the Efficacy of Inoculation to Mitigate the COVID-19 Pandemic. *Vaccines (Basel)* **2023**, *11* (2), 349. <https://doi.org/10.3390/vaccines11020349>.
23. He, K.; Mack, W. J.; Neely, M.; Lewis, L.; Anand, V. Parental Perspectives on Immunizations: Impact of the COVID-19 Pandemic on Childhood Vaccine Hesitancy. *J Community Health* **2022**, *47* (1), 39–52. <https://doi.org/10.1007/s10900-021-01017-9>.
24. McDonald, H. I.; Tessier, E.; White, J. M.; Woodruff, M.; Knowles, C.; Bates, C.; Parry, J.; Walker, J. L.; Scott, J. A.; Smeeth, L.; Yarwood, J.; Ramsay, M.; Edelstein, M. Early Impact of the Coronavirus Disease (COVID-19) Pandemic and Physical Distancing Measures on Routine Childhood Vaccinations in England, January to April 2020. *Euro Surveill* **2020**, *25* (19). <https://doi.org/10.2807/1560-7917.ES.2020.25.19.2000848>.
25. Lassi, Z. S.; Naseem, R.; Salam, R. A.; Siddiqui, F.; Das, J. K. The Impact of the COVID-19 Pandemic on Immunization Campaigns and Programs: A Systematic Review. *Int J Environ Res Public Health* **2021**, *18* (3), 988. <https://doi.org/10.3390/ijerph18030988>.
26. Alsuhaibani, M.; Alaqeel, A. Impact of the COVID-19 Pandemic on Routine Childhood Immunization in Saudi Arabia. *Vaccines (Basel)* **2020**, *8* (4), 581. <https://doi.org/10.3390/vaccines8040581>.
27. Palo, S. K.; Dubey, S.; Negi, S.; Sahay, M. R.; Patel, K.; Swain, S.; Mishra, B. K.; Bhuyan, D.; Kanungo, S.; Som, M.; Merta, B. R.; Bhattacharya, D.; Kshatri, J. S.; Pati, S. Effective Interventions to Ensure MCH (Maternal and Child Health) Services during Pandemic Related Health Emergencies (Zika, Ebola, and COVID-19): A Systematic Review. *PLoS One* **2022**, *17* (5), e0268106. <https://doi.org/10.1371/journal.pone.0268106>.
28. Kiely, M.; Mansour, T.; Brousseau, N.; Rafferty, E.; Paudel, Y. R.; Sadarangani, M.; Svenson, L. W.; Robinson, J. L.; Gagneur, A.; Driedger, S. M.; MacDonald, S. E. COVID-19 Pandemic Impact on Childhood Vaccination Coverage in Quebec, Canada. *Hum Vaccin Immunother* **2022**, *18* (1). <https://doi.org/10.1080/21645515.2021.2007707>.
29. Verrier, F.; de Lauzanne, A.; Diouf, J.-B. N.; Zo, A. Z.; Ramblière, L.; Herindrainy, P.; Sarr, F. D.; Sok, T.; Vray, M.; Collard, J.-M.; Borand, L.; Kermorvant-Duchemin, E.; Delarocque-Astagneau, E.; Guillemot, D.; Huynh, B.-T.; Randriamamonjarison, A. N.; Volahasina, T. A.; Rasoanaivo, F.; Rakotoarimanana, F. M. J.; Raheliarivao, T. B.; Randrianirina, F.; Chon, T.; Goyet, S.; Kerleguer, A.; Ngo, V.; Lach, S.; Long, P.; Tarantola, A.; Diatta, M.; Faye, J.; Seck, A.; Padget, M.; Abdou, A. Y.; Garin, B. Vaccination Coverage and Risk Factors Associated With Incomplete Vaccination Among Children in Cambodia, Madagascar, and Senegal. *Open Forum Infect Dis* **2023**, *10* (4). <https://doi.org/10.1093/ofid/ofad136>.
30. Hogan, D.; Gupta, A. Why Reaching Zero-Dose Children Holds the Key to Achieving the Sustainable Development Goals. *Vaccines (Basel)* **2023**, *11* (4), 781. <https://doi.org/10.3390/vaccines11040781>.
31. Alexander, C.; Cabrera, M.; Moore, M.; Lomazzi, M. Driving Paediatric Vaccine Recovery in Europe. *Vaccines (Basel)* **2023**, *11* (1), 184. <https://doi.org/10.3390/vaccines11010184>.
32. Causey, K.; Fullman, N.; Sorensen, R. J. D.; Galles, N. C.; Zheng, P.; Aravkin, A.; Danovaro-Holliday, M. C.; Martinez-Piedra, R.; Sodha, S. V.; Velandia-González, M. P.; Gacic-Dobo, M.; Castro, E.; He, J.; Schipp, M.; Deen, A.; Hay, S. I.; Lim, S. S.; Mosser, J. F. Estimating Global and Regional Disruptions to Routine Childhood Vaccine Coverage during the COVID-19 Pandemic in 2020: A Modelling Study. *The Lancet* **2021**, *398* (10299), 522–534. [https://doi.org/10.1016/S0140-6736\(21\)01337-4](https://doi.org/10.1016/S0140-6736(21)01337-4).
33. Wiysonge, C. S.; Uthman, O. A.; Ndumbe, P. M.; Hussey, G. D. Individual and Contextual Factors Associated with Low Childhood Immunisation Coverage in Sub-Saharan Africa: A Multilevel Analysis. *PLoS One* **2012**, *7* (5), e37905. <https://doi.org/10.1371/journal.pone.0037905>.
34. WHO. GLOBAL ROUTINE IMMUNIZATION STRATEGIES AND PRACTICES (GRISP) A Companion Document to the Global Vaccine Action Plan (GVAP); WHO: Geneva, 2016.
35. WHO. Immunization and vaccine-preventable communicable diseases <https://www.who.int/data/gho/data/themes/immunization> (accessed 2023 -11 -12).
36. Immunization and vaccine-preventable communicable diseases <https://data.unicef.org/resources/immunization-coverage-are-we-losing-ground/> (accessed 2023 -04 -29).
37. Cutts, F. T.; Izurieta, H. S.; Rhoda, D. A. Measuring Coverage in MNCH: Design, Implementation, and Interpretation Challenges Associated with Tracking Vaccination Coverage Using Household Surveys. *PLoS Med* **2013**, *10* (5), e1001404. <https://doi.org/10.1371/journal.pmed.1001404>.
38. WHO/UNICEF. Progress and Challenges with Achieving Universal Immunization Coverage. 2022 WHO/UNICEF Estimates of National Immunization Coverage (WUENIC); Geneva, 2023.
39. Brown, C. L.; Montez, K.; Amati, J. B.; Simeonsson, K.; Townsend, J. D.; Orr, C. J.; Palakshappa, D. Impact of COVID-19 on Pediatric Primary Care Visits at Four Academic Institutions in the Carolinas. *Int J Environ Res Public Health* **2021**, *18* (11), 5734. <https://doi.org/10.3390/ijerph18115734>.

40. Shet, A.; Carr, K.; Danovaro-Holliday, M. C.; Sodha, S. V.; Prospero, C.; Wunderlich, J.; Wonodi, C.; Reynolds, H. W.; Mirza, I.; Gacic-Dobo, M.; O'Brien, K. L.; Lindstrand, A. Impact of the SARS-CoV-2 Pandemic on Routine Immunisation Services: Evidence of Disruption and Recovery from 170 Countries and Territories. *Lancet Glob Health* **2022**, *10* (2), e186–e194. [https://doi.org/10.1016/S2214-109X\(21\)00512-X](https://doi.org/10.1016/S2214-109X(21)00512-X).
41. Aguinaga-Ontoso, I.; Guillen-Aguinaga, S.; Guillen-Aguinaga, L.; Alas-Brun, R.; Onambele, L.; Aguinaga-Ontoso, E.; Guillen-Grima, F. COVID-19 Impact on DTP Vaccination Trends in Africa: A Joinpoint Regression Analysis. *Vaccines (Basel)* **2023**, *11* (6), 1103. <https://doi.org/10.3390/vaccines11061103>.
42. Castrejon, M. M.; Leal, I.; de Jesus Pereira Pinto, T.; Guzmán-Holst, A. The Impact of COVID-19 and Catch-up Strategies on Routine Childhood Vaccine Coverage Trends in Latin America: A Systematic Literature Review and Database Analysis. *Hum Vaccin Immunother* **2022**, *18* (6). <https://doi.org/10.1080/21645515.2022.2102353>.
43. Munyangaju, I.; López-Varela, E.; Bassat, Q. Closing the Gap in Childhood Immunisation after the Pandemic. *BMJ* **2023**, p627. <https://doi.org/10.1136/bmj.p627>.
44. THE GLOBAL HEALTH OBSERVATORY. Immunization and vaccine-preventable communicable diseases Immunization and vaccine-preventable communicable diseases (accessed 2023 -11 -29).
45. Kaur, G.; Danovaro-Holliday, M. C.; Mwinnyaa, G.; Gacic-Dobo, M.; Francis, L.; Grevendonk, J.; Sodha, S. V.; Sugerman, C.; Wallace, A. Routine Vaccination Coverage – Worldwide, 2022. *MMWR Morb Mortal Wkly Rep* **2023**, *72* (43), 1155–1161. <https://doi.org/10.15585/mmwr.mm7243a1>.
46. World Health Assembly. Immunization Agenda 2030: A Global Strategy to Leave No One Behind.; WHO: Geneva, 2020.
47. UNICEF. COVID-19 pandemic fuels largest continued backslide in vaccinations in three decades <https://www.unicef.org/press-releases/WUENIC2022release> (accessed 2023 -05 -16).
48. Data Warehouse - UNICEF DATA https://data.unicef.org/resources/data_explorer/unicef_f/?ag=UNICEF&df=IMMUNISATION&ver=1.0&dq=.IM_DTP3..&startPeriod=2000&endPeriod=2022 (accessed 2023 -04 -18).
49. UNICEF. Number of Births. Data Warehouse - UNICEF DATA https://data.unicef.org/resources/data_explorer/unicef_f/?ag=UNICEF&df=GLOBAL_DATAFLOW&ver=1.0&dq=.DM_BRTS..&startPeriod=2019&endPeriod=2021 (accessed 2023 -05 -21).
50. World Bank. Population, total | Data <https://data.worldbank.org/indicator/SP.POP.TOTL> (accessed 2023 -05 -21).
51. White, K. J. The Durbin-Watson Test for Autocorrelation in Nonlinear Models. *Rev Econ Stat* **1992**, *74* (2), 370. <https://doi.org/10.2307/2109675>.
52. Wagner, A. K.; Soumerai, S. B.; Zhang, F.; Ross-Degnan, D. Segmented Regression Analysis of Interrupted Time Series Studies in Medication Use Research. *J Clin Pharm Ther* **2002**, *27* (4), 299–309. <https://doi.org/10.1046/j.1365-2710.2002.00430.x>.
53. Lopez Bernal, J.; Cummins, S.; Gasparrini, A. Interrupted Time Series Regression for the Evaluation of Public Health Interventions: A Tutorial. *Int J Epidemiol* **2016**, dyw098. <https://doi.org/10.1093/ije/dyw098>.
54. Slavova, S.; Rock, P.; Bush, H. M.; Quesinberry, D.; Walsh, S. L. Signal of Increased Opioid Overdose during COVID-19 from Emergency Medical Services Data. *Drug Alcohol Depend* **2020**, *214*, 108176. <https://doi.org/10.1016/j.drugalcdep.2020.108176>.
55. Joinpoint Regression Program. Version 4.3.1.0. April, 2016; Statistical Methodology and Applications Branch, Surveillance Research Program, National Cancer Institute.
56. Kim, H. J.; Fay, M. P.; Feuer, E. J.; Midthune, D. N. Permutation Tests for Joinpoint Regression with Applications to Cancer Rates. *Stat Med* **2000**, *19* (3), 335–351. [https://doi.org/10.1002/\(SICI\)1097-0258\(20000215\)19:3<335::AID-SIM336>3.0.CO;2-Z](https://doi.org/10.1002/(SICI)1097-0258(20000215)19:3<335::AID-SIM336>3.0.CO;2-Z).
57. Muggeo, V. M.; Atkins, D. C.; Gallop, R. J.; Dimidjian, S. Segmented Mixed Models with Random Change-points: A Maximum Likelihood Approach with Application to Treatment for Depression Study. *Stat Modelling* **2014**, *14* (4), 293–313. <https://doi.org/10.1177/1471082X13504721>.
58. Muggeo, V. M. R. Interval Estimation for the Breakpoint in Segmented Regression: A Smoothed Score-based Approach. *Aust N Z J Stat* **2017**, *59* (3), 311–322. <https://doi.org/10.1111/anzs.12200>.
59. Muggeo, V. M. R. Testing with a Nuisance Parameter Present Only under the Alternative: A Score-Based Approach with Application to Segmented Modelling. *J Stat Comput Simul* **2016**, *86* (15), 3059–3067. <https://doi.org/10.1080/00949655.2016.1149855>.
60. Fasola, S.; Muggeo, V. M. R.; Küchenhoff, H. A Heuristic, Iterative Algorithm for Change-Point Detection in Abrupt Change Models. *Comput Stat* **2018**, *33* (2), 997–1015. <https://doi.org/10.1007/s00180-017-0740-4>.
61. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna, Austria. 2023.
62. RStudio Team. RStudio: Integrated Development for R. RStudio, PBC.; Boston, MA. 2023.
63. Wickham, H. *Ggplot2: Elegant Graphics for Data Analysis*; Springer-Verlag : New York, 2016.
64. Wickham, H.; Bryan, J. Readxl: Read Excel Files. R Package Version 1.4.3. 2023.
65. Mapchart Version 4.3.2. Mapchart . November 30, 2023.

66. Brewer, C. A.; Hatchard, G. W.; Harrower, M. A. ColorBrewer in Print: A Catalog of Color Schemes for Maps. *Cartogr Geogr Inf Sci* **2003**, *30* (1), 5–32. <https://doi.org/10.1559/152304003100010929>.
67. Brewer, C. A.; Hatchard, G. W.; Harrower, M. A. COLORBREWER 2.0 Color Advice for Cartograph. 2013.
68. Rau, C.; Lüdecke, D.; Dumolard, L. B.; Grevendonk, J.; Wiernik, B. M.; Kobbe, R.; Gacic-Dobo, M.; Danovaro-Holliday, M. C. Data Quality of Reported Child Immunization Coverage in 194 Countries between 2000 and 2019. *PLOS Global Public Health* **2022**, *2* (2), e0000140. <https://doi.org/10.1371/journal.pgph.0000140>.
69. Bower, M.; Kothari, U.; Akerman, M.; Krilov, L. R.; Fiorito, T. M. Impact of COVID-19 on HPV Vaccination Rates in New York City and Long Island. *Pediatric Infectious Disease Journal* **2023**. <https://doi.org/10.1097/INF.0000000000004149>.
70. Urueña, A.; Machado, R.; Cunha, J.; López Colmano, C.; Rancaño, C.; Kfourri, R.; Pérez, C.; Bonvehí, P.; Calvo, M.; Cuadros, R.; Muñoz, G.; Rodríguez, M.; Torres, J.; Cahn, F.; Ballalai, I. Opinions, Attitudes and Factors Related to SARS-CoV-2 Vaccine Uptake in Eight South American Countries. *Vaccines (Basel)* **2023**, *11* (11), 1660. <https://doi.org/10.3390/vaccines11111660>.
71. Mwinnyaa, G.; Peters, M. A.; Shapira, G.; Neill, R.; Sadat, H.; Yuma, S.; Akilimali, P.; Hossain, S.; Wendrad, N.; Atiwoto, W. K.; Ofosu, A. A.; Alfred, J. P.; Kiarie, H.; Wesseh, C. S.; Isokpunwu, C.; Kangbai, D. M.; Mohamed, A. A.; Sidibe, K.; Drouard, S.; Fernandez, P. A.; Azais, V.; Hashemi, T.; Hansen, P. M.; Ahmed, T. Vaccination Utilization and Subnational Inequities during the COVID-19 Pandemic: An Interrupted Time-Series Analysis of Administrative Data across 12 Low- and Middle-Income Countries. *Vaccines (Basel)* **2023**, *11* (9), 1415. <https://doi.org/10.3390/vaccines11091415>.
72. Muhoza, P.; Danovaro-Holliday, M. C.; Diallo, M. S.; Murphy, P.; Sodha, S. V.; Requejo, J. H.; Wallace, A. S. Routine Vaccination Coverage — Worldwide, 2020. *MMWR Morb Mortal Wkly Rep* **2021**, *70* (43), 1495–1500. <https://doi.org/10.15585/mmwr.mm7043a1>.
73. Evans, B.; Keiser, O.; Kaiser, L.; Jombart, T. Analysis of Global Routine Immunisation Coverage Shows Disruption and Stagnation during the First Two-Years of the COVID-19 Pandemic with Tentative Recovery in 2022. *Vaccine X* **2023**, *15*, 100383. <https://doi.org/10.1016/j.jvax.2023.100383>.
74. LaMori, J.; Feng, X.; Pericone, C. D.; Mesa-Frias, M.; Sogbetun, O.; Kulczycki, A. Hepatitis Vaccination Adherence and Completion Rates and Factors Associated with Low Compliance: A Claims-Based Analysis of U.S. Adults. *PLoS One* **2022**, *17* (2), e0264062. <https://doi.org/10.1371/journal.pone.0264062>.
75. Périères, L.; Séror, V.; Boyer, S.; Sokhna, C.; Peretti-Watel, P. Reasons given for Non-Vaccination and under-Vaccination of Children and Adolescents in Sub-Saharan Africa: A Systematic Review. *Hum Vaccin Immunother* **2022**, *18* (5). <https://doi.org/10.1080/21645515.2022.2076524>.
76. Atnafu Gebeyehu, N.; Abebe Gelaw, K.; Asmare Adella, G.; Dagnaw Tegegne, K.; Adie Admass, B.; Mesele Gesese, M. Incomplete Immunization and Its Determinants among Children in Africa: Systematic Review and Meta-Analysis. *Hum Vaccin Immunother* **2023**. <https://doi.org/10.1080/21645515.2023.2202125>.
77. Tan, L. (L. J.); Safadi, M. A. P.; Horn, M.; Regojo Balboa, C.; Moya, E.; Schanbaum, J.; Pimenta, P.; Lambert, E.; Soumahoro, L.; Sohn, W.-Y.; Bruce, T.; Ruiz García, Y. Pandemic's Influence on Parents' Attitudes and Behaviors toward Meningococcal Vaccination. *Hum Vaccin Immunother* **2023**, *19* (1). <https://doi.org/10.1080/21645515.2023.2179840>.
78. Bonanni, P.; Steffen, R.; Schelling, J.; Balaisyte-Jazone, L.; Posiuniene, I.; Zatoński, M.; Van Damme, P. Vaccine Co-Administration in Adults: An Effective Way to Improve Vaccination Coverage. *Hum Vaccin Immunother* **2023**, *19* (1). <https://doi.org/10.1080/21645515.2023.2195786>.
79. Evans, W. D.; Bingenheimer, J. B.; Long, M.; Ndiaye, K.; Donati, D.; Rao, N. M.; Akaba, S.; Nsofor, I.; Agha, S. Outcomes of a Social Media Campaign to Promote COVID-19 Vaccination in Nigeria. *PLoS One* **2023**, *18* (9), e0290757. <https://doi.org/10.1371/journal.pone.0290757>.
80. Diedrich, D., Northcote, N., Röder, T., & Sauer-Sidor, K. Strategic resilience during the COVID-19 crisis | McKinsey <https://www.mckinsey.com/capabilities/strategy-and-corporate-finance/our-insights/strategic-resilience-during-the-covid-19-crisis> (accessed 2023 -04 -29).
81. WHO and UNICEF warn of a decline in vaccinations during COVID-19 <https://www.who.int/news/item/15-07-2020-who-and-unicef-warn-of-a-decline-in-vaccinations-during-covid-19> (accessed 2023 -04 -29).
82. Watts, E.; Mak, J.; Patenaude, B. Benefit-Cost Ratios of Continuing Routine Immunization During the COVID-19 Pandemic in Africa. *J Benefit Cost Anal* **2022**, *13* (1), 91–106. <https://doi.org/10.1017/bca.2021.13>.
83. de Oliveira Roque e Lima, J.; Pagotto, V.; Rocha, B. S.; Scalize, P. S.; Guimarães, R. A.; de Lima, M. D.; da Silva, L. N.; da Silva Oliveira, M. D.; Moura, W. É. A.; Teles, S. A.; Rosso, C. F. W.; Caetano, K. A. A. Low Vaccine Coverage and Factors Associated with Incomplete Childhood Immunization in Racial/Ethnic Minorities and Rural Groups, Central Brazil. *Vaccines (Basel)* **2023**, *11* (4), 838. <https://doi.org/10.3390/vaccines11040838>.
84. Tan, N. C.; Pang, J.; Koh, E. The Impact of a Revised National Childhood Immunization Schedule on Vaccination Defaulters. *Vaccines (Basel)* **2023**, *11* (4), 859. <https://doi.org/10.3390/vaccines11040859>.

85. Saxena, K.; Marden, J. R.; Carias, C.; Bhatti, A.; Patterson-Lomba, O.; Gomez-Lievano, A.; Yao, L.; Chen, Y.-T. Impact of the COVID-19 Pandemic on Adolescent Vaccinations: Projected Time to Reverse Deficits in Routine Adolescent Vaccination in the United States. *Curr Med Res Opin* **2021**, *37* (12), 2077–2087. <https://doi.org/10.1080/03007995.2021.1981842>.
86. Patel Murthy, B.; Zell, E.; Kirtland, K.; Jones-Jack, N.; Harris, L.; Sprague, C.; Schultz, J.; Le, Q.; Bramer, C. A.; Kuramoto, S.; Cheng, I.; Woinarowicz, M.; Robison, S.; McHugh, A.; Schauer, S.; Gibbs-Scharf, L. Impact of the COVID-19 Pandemic on Administration of Selected Routine Childhood and Adolescent Vaccinations – 10 U.S. Jurisdictions, March–September 2020. *MMWR Morb Mortal Wkly Rep* **2021**, *70* (23), 840–845. <https://doi.org/10.15585/mmwr.mm7023a2>.
87. Moraga-Llop, F. A.; Fernández-Prada, M.; Grande-Tejada, A. M.; Martínez-Alcorta, L. I.; Moreno-Pérez, D.; Pérez-Martín, J. J. Recovering Vaccine Coverage Lost Due to the COVID-19 Pandemic. *Vacunas (English Edition)* **2020**, *21* (2), 129–135. <https://doi.org/10.1016/j.vacune.2020.10.004>.
88. WHO. Scale-up routine immunization along with COVID-19 vaccination: WHO <https://www.who.int/southeastasia/news/detail/08-09-2021-scale-up-routine-immunization-along-with-covid-19-vaccination-who> (accessed 2023 -04 -29).
89. Berhane, H. Y.; Worku, A.; Fawzi, W. Effect of COVID-19 on Routine Childhood Vaccination in Bahir Dar City, Northwestern, Ethiopia. *Vaccines (Basel)* **2023**, *11* (10), 1569. <https://doi.org/10.3390/vaccines11101569>.

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