

Article

Not peer-reviewed version

Has COVID-19 Affected DTP3 Vaccination in the Americas?

[Ines Aguinaga-Ontoso](#) ^{*}, [Sara Guillén-Aguinaga](#), Laura Guillén-Aguinaga, [Rosa Alas-Brun](#), [Enrique Aguinaga-Ontoso](#), [Esperanza Rayón-Valpuesta](#), [Francisco Guillén-Grima](#) ^{*}

Posted Date: 28 December 2023

doi: 10.20944/preprints202312.0671.v2

Keywords: DTP vaccine; America; COVID-19; Vaccine coverage; Joinpoint regression; Health care system; Vaccination rates; Trends; Segmented regression



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Article

Has COVID-19 Affected DTP3 Vaccination in the Americas?

Ines Aguinaga-Ontoso ^{1,2,*}, Sara Guillén-Aguinaga ^{1,3}, Laura Guillén-Aguinaga ^{1,4}, Rosa Alas-Brun ¹, Enrique Aguinaga-Ontoso ⁵, Esperanza Rayón-Valpuesta ⁶ and Francisco Guillen-Grima ^{1,2,7,8,*}

¹ Department of Health Sciences, Public University of Navarra, 31008 Pamplona, Spain; sguillen.4@alumni.unav.es (S.G.-A.); guillen.124514@e.unavarra.es (L.G.-A.); rosamaria.alas@unavarra.es (R.A.-B.)

² Healthcare Research Institute of Navarra (IdiSNA), 31008 Pamplona, Spain

³ San Juan Primary Health Care Center, Navarra Health Service, 31008 Pamplona, Spain

⁴ Department of Nursing, Kystad Helse-og Velferdssenter, 7026 Trondheim, Norway

⁵ Department of Sociosanitary Sciences, University of Murcia, Murcia, Spain; aguinaga@um.es

⁶ Department of Nursing, Complutense University of Madrid, 28040 Madrid, Spain; erayon@ucm.es

⁷ Department of Preventive Medicine, Clínica Universidad de Navarra, 31008 Pamplona, Spain

⁸ CIBER in Epidemiology and Public Health (CIBERESP), Institute of Health Carlos III, 46980 Madrid, Spain

* Correspondence: ines.aguinaga@unavarra.es (I.A.-O.); frguillen@unav.es (F.G.-G.)

Abstract: Background: In the Americas, deaths by diseases avoidable with vaccines are 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].

The Americas ranks as the second-worst region globally regarding vaccine coverage [38–40]. 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 [41].

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 [42]. Recent data points to

a substantial impact of the COVID-19 pandemic on DTP vaccination trends [43]. 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 [44].

Similarly, a decline in vaccination coverage for multiple vaccines was observed in Latin America, with catch-up strategies implemented to address missed vaccinations [45]. 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 [46]. 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 [35,47]. 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 [48]. 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 [49].

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 [46,49].

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 [50]. 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 [46].

2. Materials and Methods

Vaccine coverage data for individual countries were sourced from the United Nations Children's Fund., databases from 2012 through 2022 [51]. We omitted the following territories: French Guiana, Greenland, Alaska, Anguilla, Aruba, Bermuda, Bonaire, Curaçao, and Guadeloupe. We also acquired regional estimates from the United Nations Children's Fund database [51]. The information regarding the annual count of newborns by country was gathered from the United Nations Children's Fund database [52] and the World Bank [53].

2.1. Regional Analysis

Regional aggregated data for North America, Latin America, and the Caribbean were obtained from the United Nations Children's Fund. Due to the absence of regional data from South America, Central America, and the Caribbean in the United Nations Children's Fund data, we calculated these figures using birth-weighted vaccination rates. This method of calculating data, based on the births in each country, was essential for deriving accurate estimations of DTP3 vaccination coverage in these

regions. The countries included in each region were as follows: In Central America, the countries were the Republic of Guatemala, the Republic of Panama, the Republic of Costa Rica, the Republic of Nicaragua, the Republic of El Salvador, the Republic of Honduras, and Belize. In North America, the countries assessed included the United States of America, the United Mexican States, and Canada. The Caribbean region's analysis encompassed Jamaica, Saint Lucia, Grenada, the Bahamas, the Republic of Cuba, Saint Vincent and the Grenadines, Barbados, the Republic of Haiti, the Republic of Trinidad and Tobago, the Dominican Republic, the Federation of Saint Kitts and Nevis, Antigua and Barbuda, and the Commonwealth of Dominica. Lastly, in South America, the countries involved were the Federative Republic of Brazil, the Republic of Chile, the Bolivarian Republic of Venezuela, the Republic of Peru, the Argentine Republic, the Republic of Ecuador, the Plurinational State of Bolivia, the Republic of Colombia, Uruguay, Paraguay, Suriname, and Guyana.

2.2. Statistical Analysis

We utilized Joinpoint regression, a methodology that has previously been applied in the examination of vaccination trends [44]. We calculated the annual percentage change (APC) to gauge the extent of variation in each trend. In these statistical models, the vaccine coverage was the dependent variable, while the year was the independent variable. The models assumed constant variance (homoscedasticity). We conducted a Durbin-Watson test to evaluate the presence of autocorrelation within the time series data [54]. First-order autocorrelation estimated from the data was computed in all the cases.

We employed an interrupted time series analysis method. This technique is considered the most effective quasi-experimental approach for assessing the impact of external events or interventions, such as the COVID-19 pandemic [55–57]. Our study had eleven years, eight years preCovid (2012–2019), and three years, 2020–2022, post-Covid. The model of the analysis follows the equation below.

$$DTP3_t = \text{Intercept} + \beta_1 \text{Year} + \beta_2 \text{COVID19} + \beta_3 \text{YearCOVID19} + \varepsilon_t \quad (1)$$

where “DTP3” is the number of doses administered, Year is the year of the calendar, COVID19 is a dummy variable that has value “1” for the pandemic years (2020–22); “YearCOVID19” is an interaction between Year and the COVID-19. Furthermore, we compared DTP3 vaccination coverage for each country in 2019 and its respective coverage data in 2022. Our examination of DTP3 vaccination coverage across American countries involved a comparison of coverage rates for 2019 and 2022. To achieve this, we employed the Chi-Square test.

2.3. Software

All Joinpoint analysis calculations were performed utilizing Joinpoint (Version 5.0.2, May 2023) [58,59]. The statistical comparison of rates between 2019 and 2022 was conducted using the IBM Statistical Package for the Social Sciences, version 27 (IBM Corp., Armonk, NY, USA). The interrupted time series analysis was computed using the “segmented” [60–63] package in R (version 4.3.1, 2023-06-16 ucrt)[64], under Rstudio (Version 2023.09.1 Build 494) [65]. This was complemented using the ‘ggplot2’ package for advanced graphical representations [66] and the ‘readxl’ package for seamlessly importing Excel data files [67]. Maps were created with Mapchart (v 4.3.2.) [68]. The scale of colors for the maps was elaborated with Colorbrewer (v.2.0) [69,70].

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

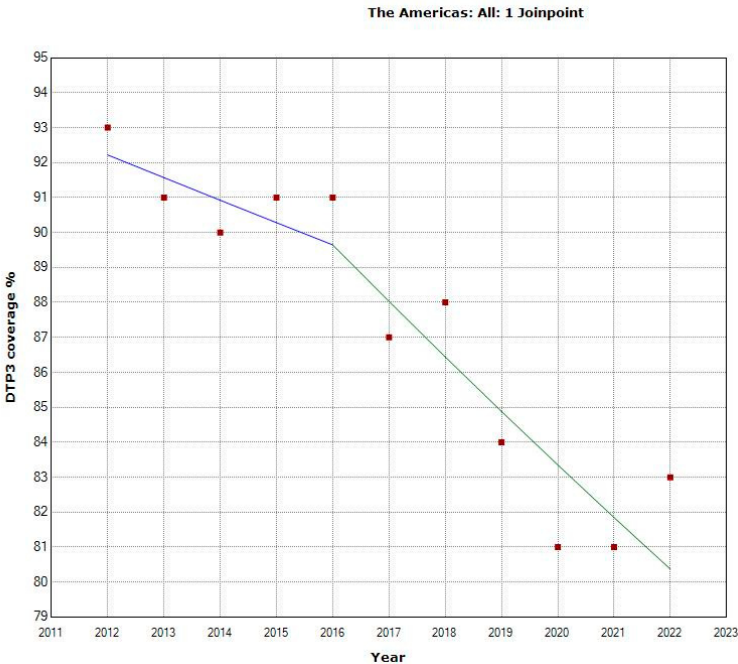


Figure 1. Joinpoint graph of DTP3 in the Americas (2012-22).

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. DTP3 Joinpoint in American regions, 2012–22.

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

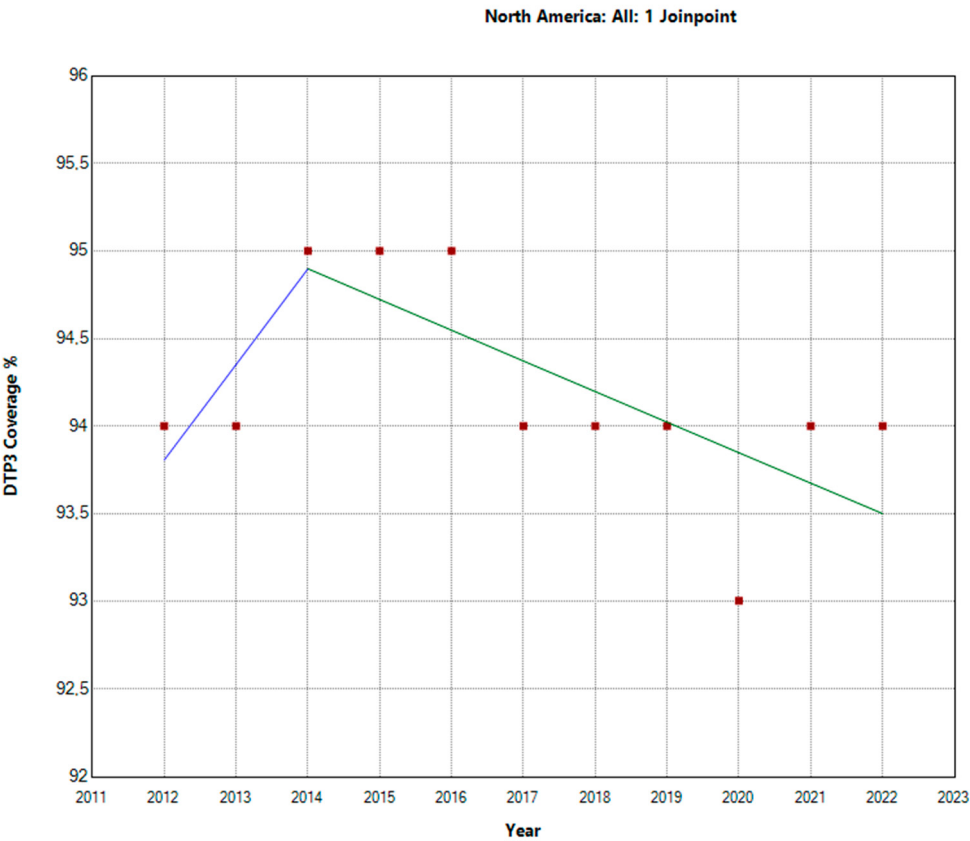


Figure 2. Joinpoint graph of DTP3 in North America (2012-22).

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 Joinpoint 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, 5, and 6, illustrating the third DTP dose vaccination rate trends in Central America, the Caribbean, and South America, respectively, highlighting the Joinpoints.

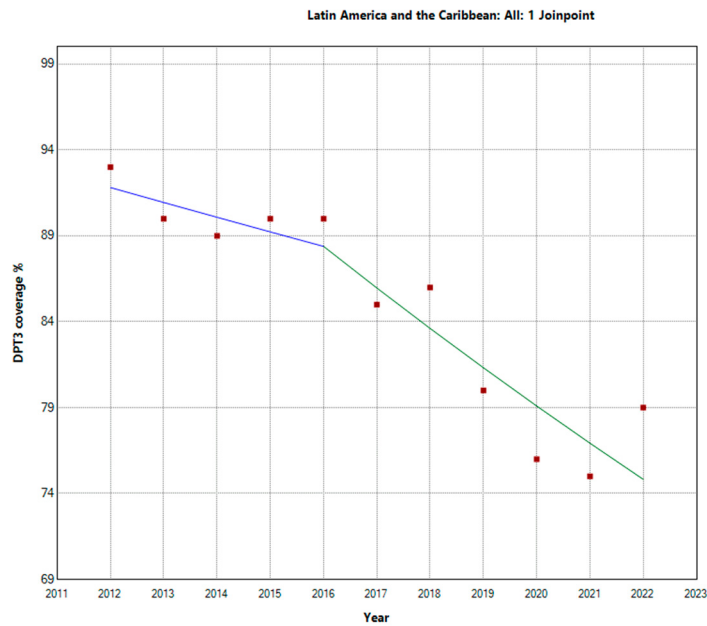


Figure 3. Joinpoint graph of DTP3 in Latin America and the Caribbean (2012-22).

During the research period spanning from 2012 to 2022, there were notable variations in the vaccination rates for the third dose of DTP across different areas 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).

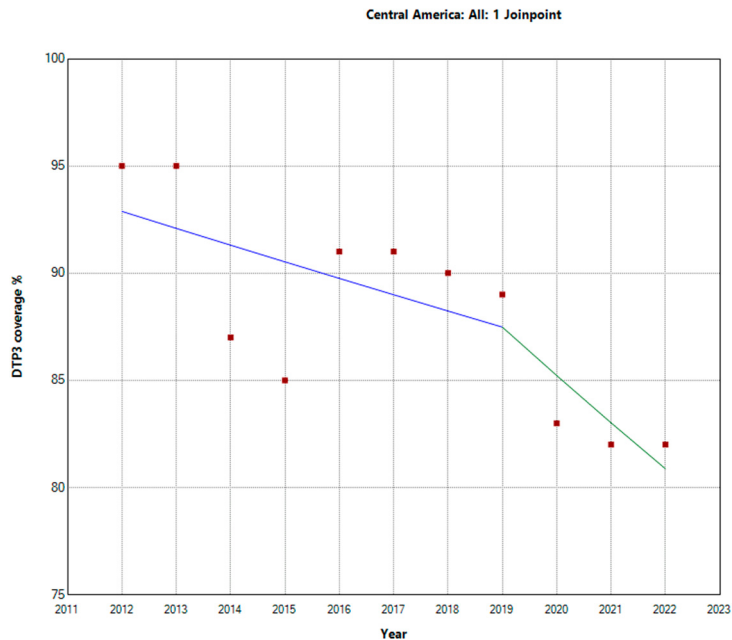


Figure 4. Joinpoint graph of DTP3 in Central America. (2012-22).

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 (Figure 5). 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).

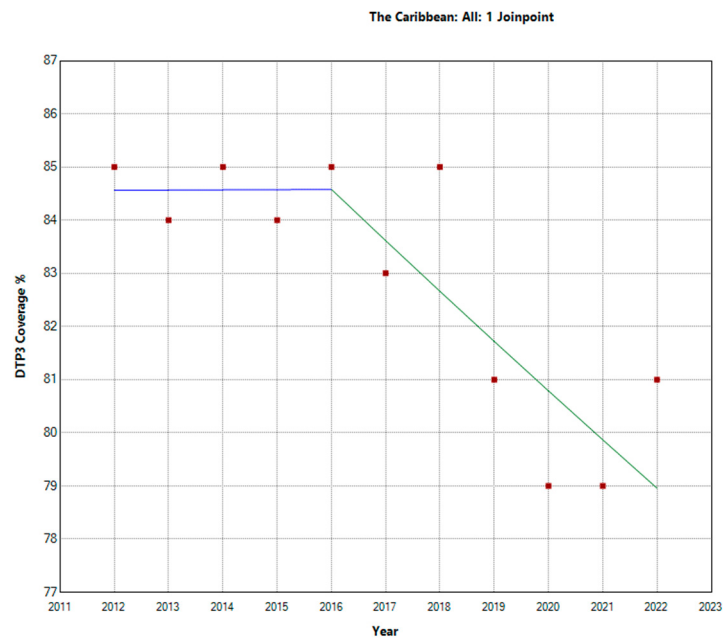


Figure 5. Joinpoint graph of DTP3 in the Caribbean (2012-22).

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 (Figure 6). The trend intensified in the second period (2015-2022), with an APC of -3.1% (95% CI -4.4, -1.8; P=0.001).

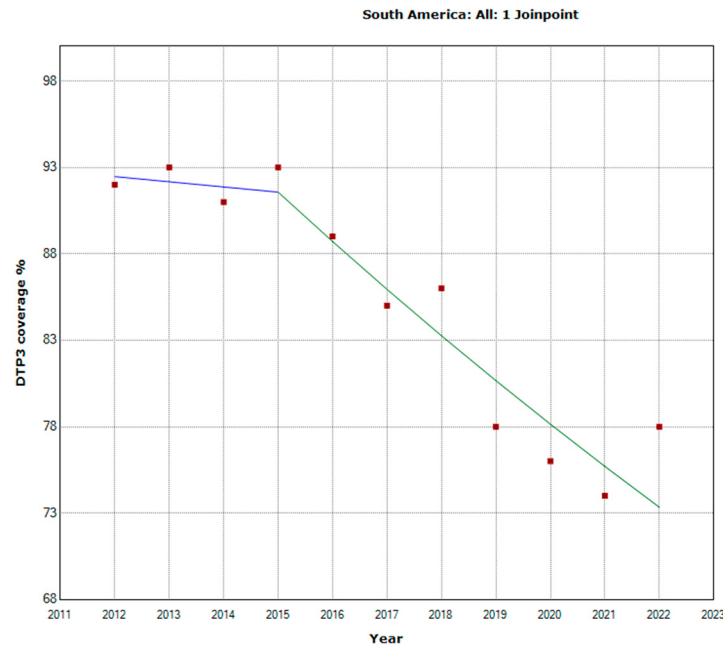


Figure 6. Joinpoint graph of DTP3 in South America (2012-22).

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 7). The Americas experienced a 4% reduction in DTP3 vaccine coverage from 2019 to 2022. However, vaccine coverage rates remained unchanged in North America, South America, and the Caribbean.

In contrast, Central America witnessed a more substantial decline in vaccine coverage, with a decrease of 7% (Table 3).

Table 3. Changes in DTP3 rate (%) in American Regions between 2019-22.

Region	2019	2020	2021	2022	Absolute Changes 2019–2022	Relative Changes 2019–2022
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%

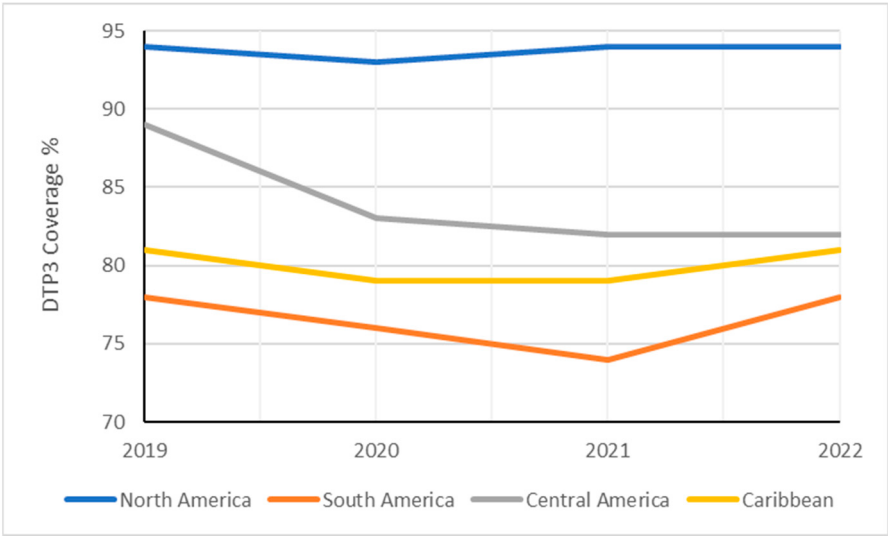


Figure 7. Evolution of DTP3 rates(2012-22) in South America by Regions.

Table 4 displays the DTP3 rates for the years 2019 and 2022. On average, there was a reduction of -4.20% across countries, with a standard deviation of 6.08, and this change was statistically significant at $p < 0.001$. 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. Changes in DTP3 rates (%) Across American Countries 2019-22.

Country	2019		2022		p^+
	DTP3 (%)	Births (n)	DTP3 (%)	Births (n)	
Antigua and Barbuda	95	1058	99	1124	<0.001
Argentina	83	661385	81	627741	<0.001
Bahamas	89	4641	87	4659	ns
Barbados	90	3050	86	3037	ns
Belize	98	7333	84	7193	0.003
Bolivia	75	263006	69	264070	<0.001
Brazil	70	2886359	77	2723266	<0.001
Canada	91	363393	92	376188	ns
Chile	96	224350	96	230824	ns

Colombia	94	733940	87	723264	<0.001
Costa Rica	95	65282	95	60517	ns
Cuba	99	110404	99	99693	ns
Dominica	99	946	92	966	ns
Dominican Republic	89	210196	88	203625	ns
Ecuador	85	300075	70	298666	<0.001
El Salvador	90	103547	75	100313	<0.001
Grenada	94	2041	77	1960	0.054
Guatemala	85	391582	79	372335	<0.001
Guyana	99	16898	98	16129	ns
Haiti	51	271669	51	268523	ns
Honduras	88	215469	78	217590	<0.001
Jamaica	96	33815	98	32663	ns
Mexico	82	1965139	83	1866399	<0.001
Nicaragua	98	142181	92	139164	<0.001
Panama	88	77044	87	76637	ns
Paraguay	86	139138	69	137960	<0.001
Peru	88	591025	82	592156	<0.001
Saint Kitts and Nevis	97	607	96	563	ns
Saint Lucia	92	2113	81	2035	ns
Saint Vincent and the Grenadines	97	1405	92	1324	ns
Suriname	77	11049	77	11123	ns
Trinidad and Tobago	93	18904	93	17429	ns
Uruguay	94	3756830	94	3726867	ns
United States	94	37107	94	35668	ns
Venezuela	64	497361	56	438384	<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, Guyana, El Salvador, Nicaragua, Saint Lucia, Paraguay, Saint Vincent and the Grenadines, Ecuador, Honduras, Venezuela, Guatemala, Panama, Grenada, Peru, Dominica, and the Dominican Republic). The Dominican Republic, Guyana, Panama, Saint Kitts and Nevis experienced a 1% decrease, while Argentina faced a 2% decline. In nations with declining vaccination coverage, the average absolute decrease was -7.37% (with a standard deviation of 5.39), statistically significant at a significance level of $P < 0.01$. (Table 4) (Figures 8, 9 and 10).

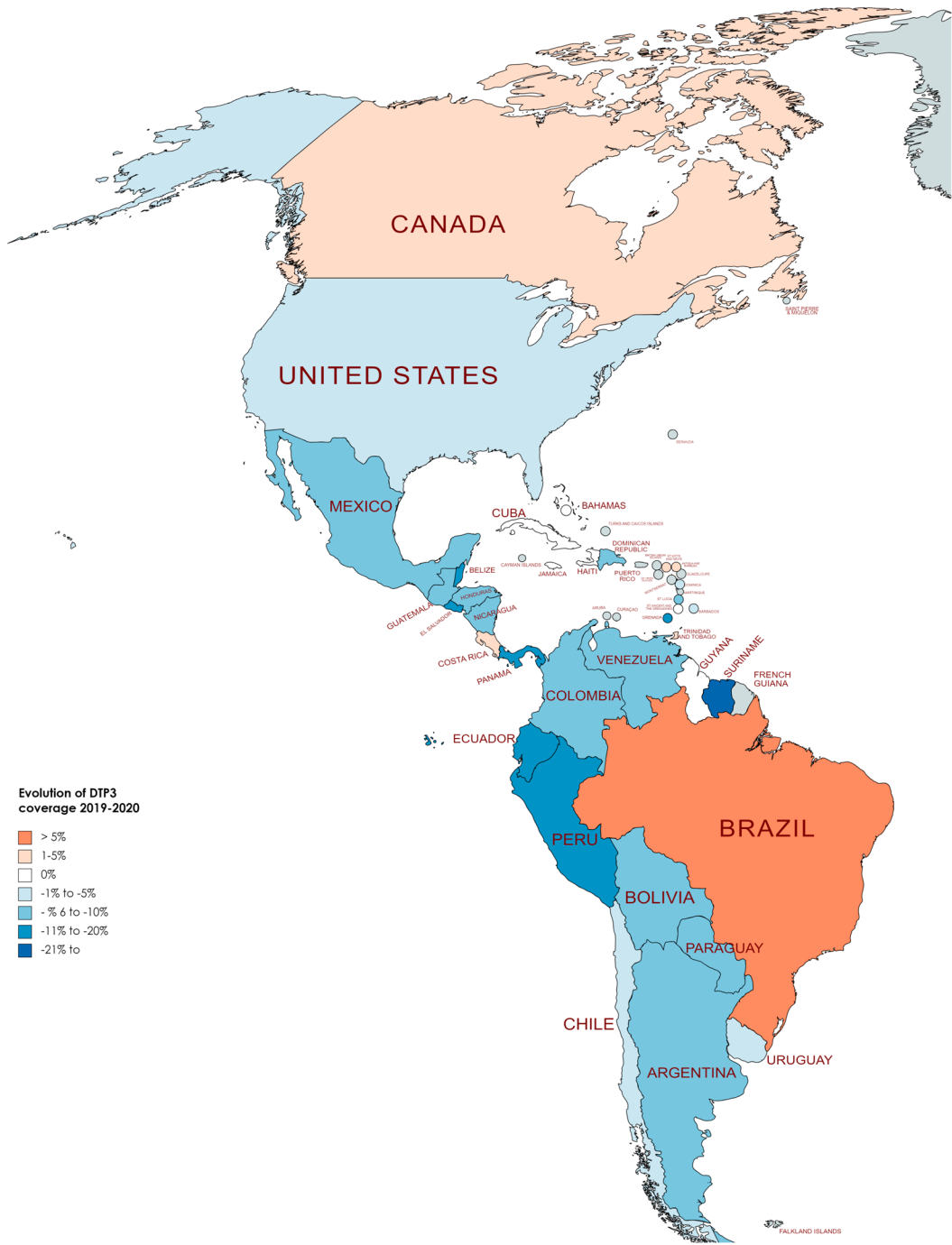


Figure 8. Changes in DTP3 Coverage (%) in America 2019-20.



Figure 9. Changes in DTP3 Coverage (%) in America 2019-21.



Figure 10. Changes in DTP3 Coverage (%) in America 2019-22.

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).

We found that in 2019, a total of 19 countries in the Americas, namely the United States, Canada, Chile, Uruguay, Trinidad and Tobago, Saint Vincent and the Grenadines, Saint Kitts and Nevis, Saint Lucia, Nicaragua, Jamaica, Guyana, Grenada, El Salvador, Dominica, Cuba, Costa Rica, Colombia, Belize, Barbados, and Antigua and Barbuda, had successfully achieved the World Health Organization’s goal of attaining at least 90% coverage for the third dose of the DTP vaccine by the

year 2030. After the pandemic, by 2022, it was observed that six nations—Barbados, Belize, Colombia, El Salvador, Grenada, and Saint Lucia—no longer met the 90% coverage target for the DTP vaccine. This was a change from the list of countries that had achieved this goal in 2019 (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% IC 2014–2020). In five countries, Canada, Ecuador, Grenada, Jamaica, Nicaragua, and Paraguay, the Joinpoint was in 2018 (95% IC 2016–2019). In three countries, Belize, Colombia, and Saint Lucia, there was a Joinpoint in 2019 (95% IC 2017–2020). Finally, there were six countries: Bahamas, Dominica, Mexico, Saint Kitts and Nevis, Suriname, and Uruguay, with a Joinpoint in 2020 (95% IC 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 rates 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

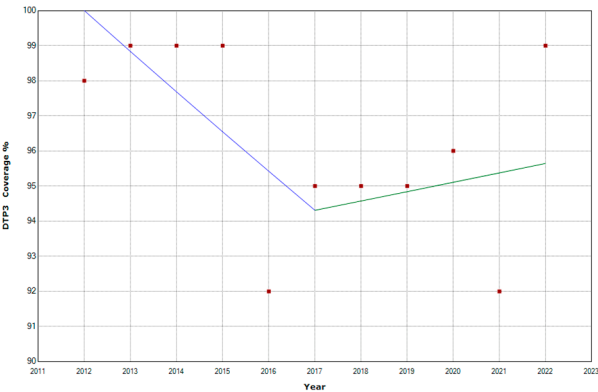


Figure 13. Joinpoint graph of DTP3 in Antigua and Barbuda (2012-22).

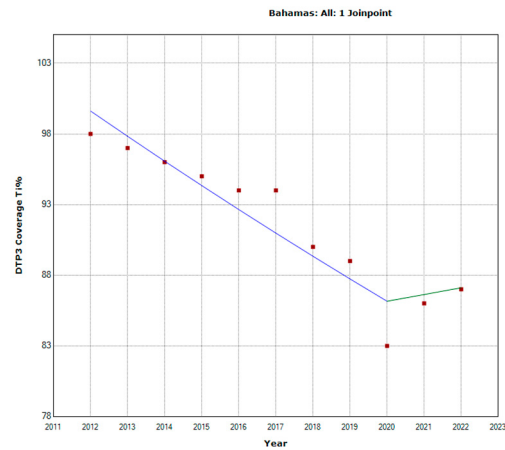


Figure 14. Joinpoint graph of DTP3 in the Bahamas. (2012-22).

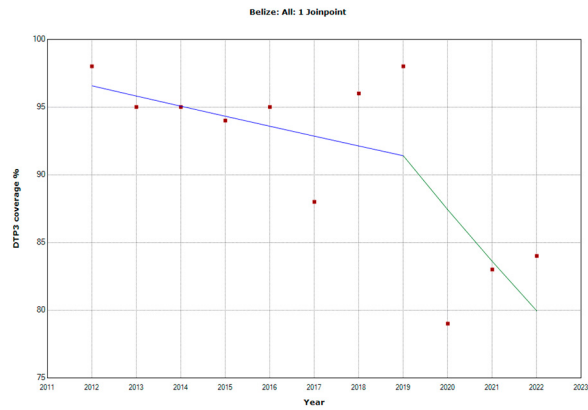


Figure 15. Joinpoint graph of DTP3 in Belize. (2012-22).

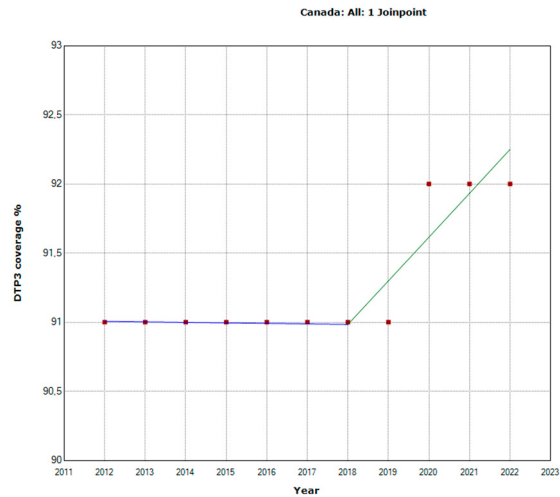


Figure 16. Joinpoint graph of DTP3 in Canada (2012-22).

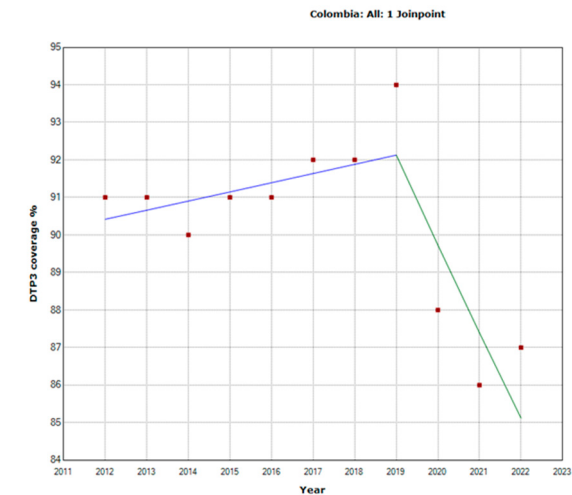


Figure 17. Joinpoint graph of DTP3 in Colombia (2012-22).

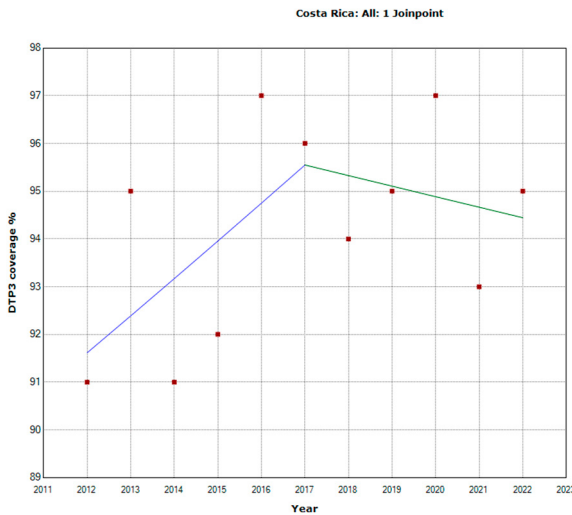


Figure 18. Joinpoint graph of DTP3 in Costa Rica (2012-22).

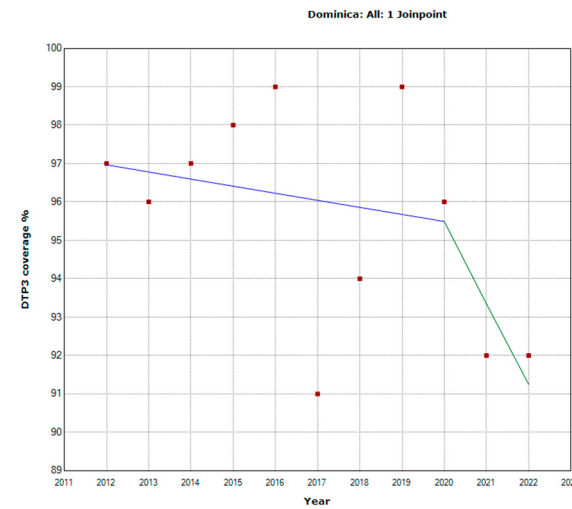


Figure 19. Joinpoint graph of DTP3 in Dominica (2012-22).

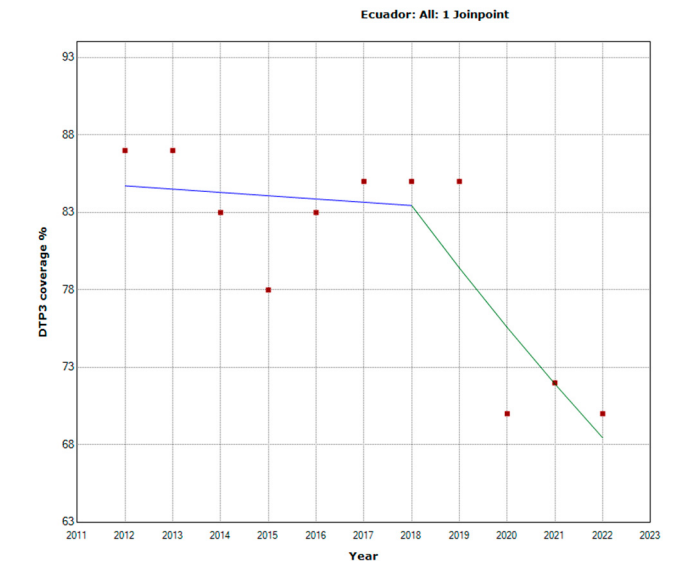


Figure 20. Joinpoint graph of DTP3 in Ecuador (2012-22).

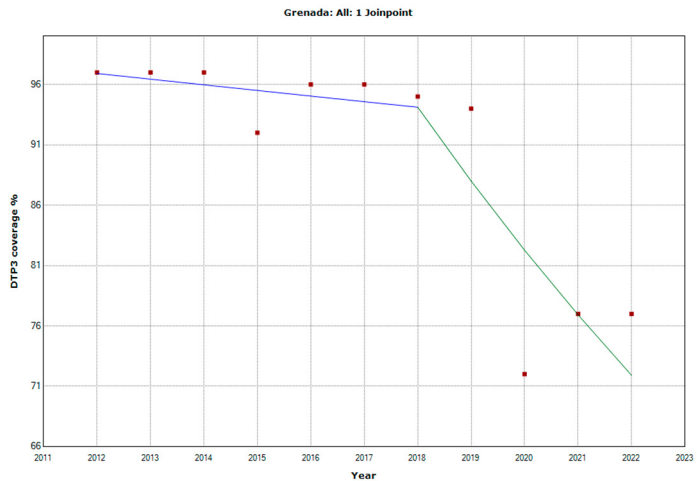


Figure 21. Joinpoint graph of DTP3 in Grenada (2012-22).

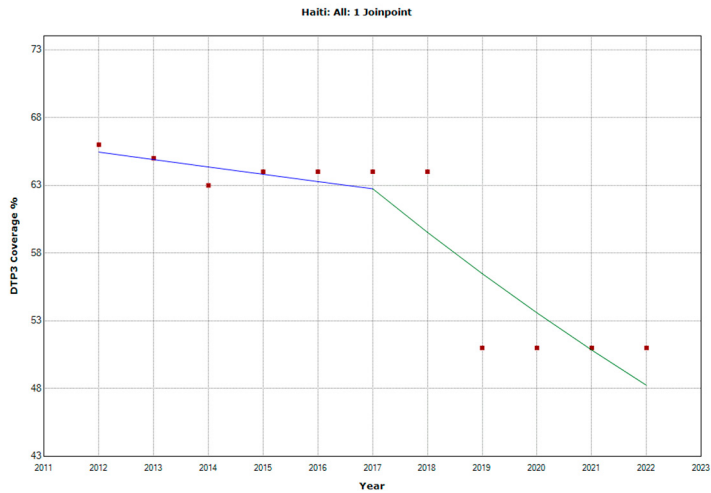


Figure 22. Joinpoint graph of DTP3 in Haiti (2012-22).

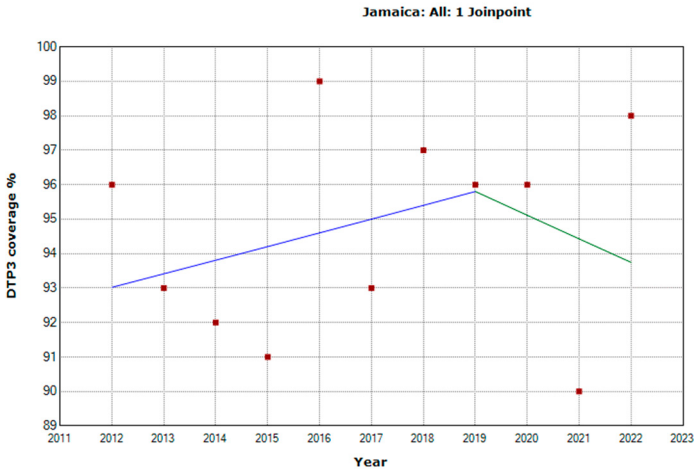


Figure 23. Joinpoint graph of DTP3 in Jamaica (2012-22).

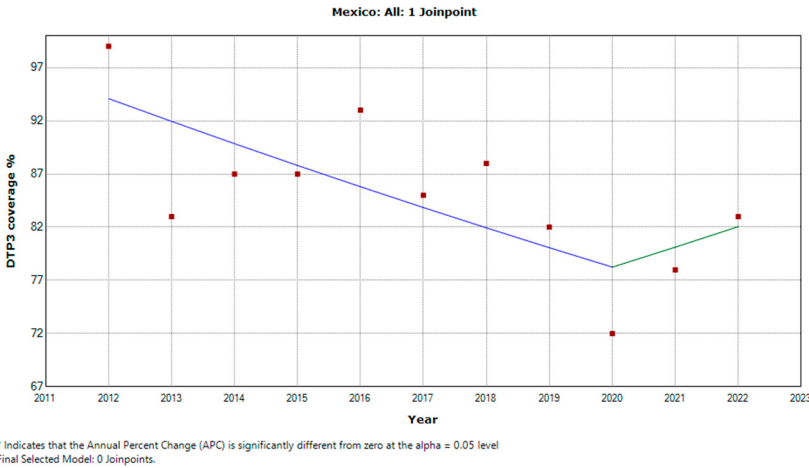


Figure 24. Joinpoint graph of DTP3 in Mexico. (2012-22).

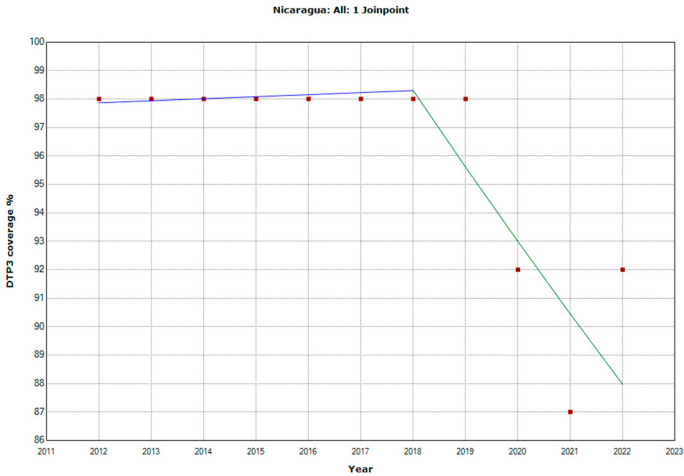


Figure 25. Joinpoint graph of DTP3 in Nicaragua (2012-22).

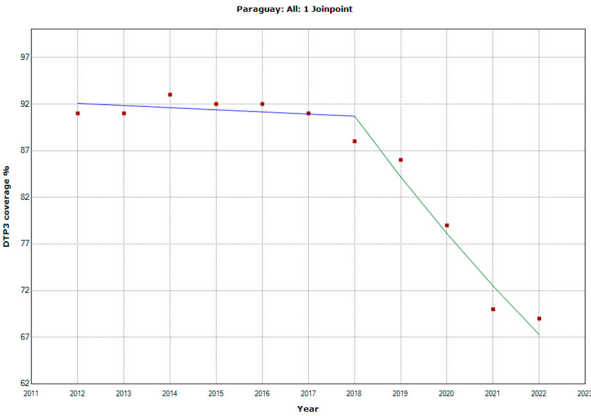


Figure 26. Joinpoint graph of DTP3 in Paraguay (2012-22).

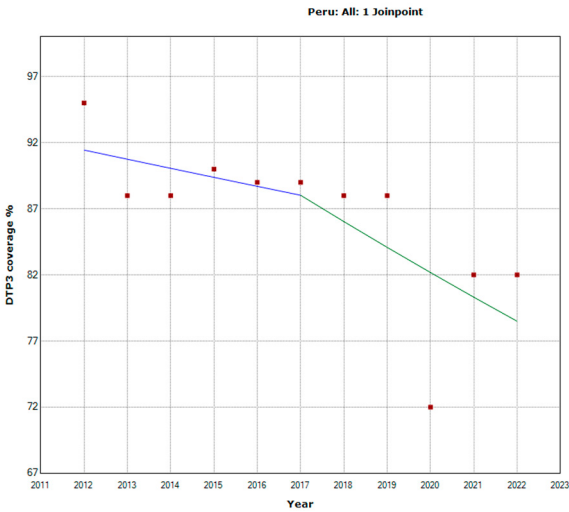


Figure 27. Joinpoint graph of DTP3 in Peru (2012-22).

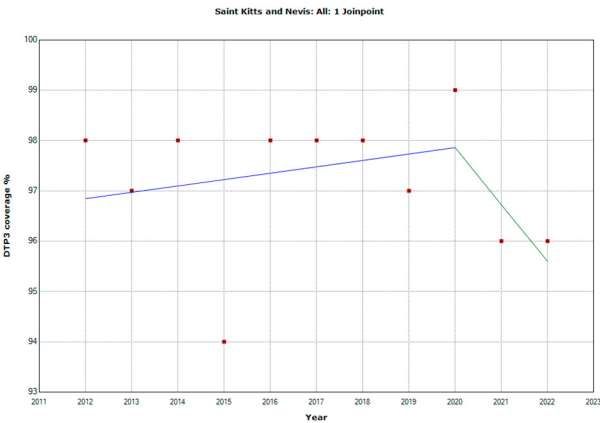


Figure 28. Joinpoint graph of DTP3 in Saint Kitts and Nevis (2012-22).

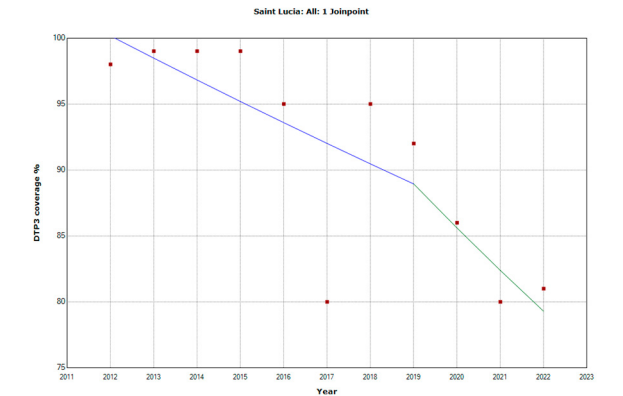


Figure 29. Joinpoint graph of DTP3 in Saint Lucia (2012-22).

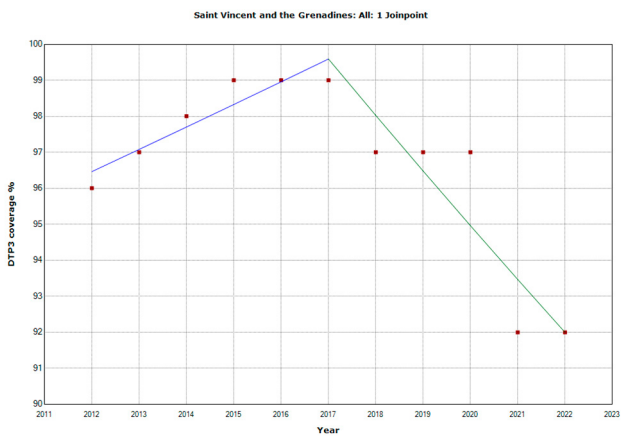


Figure 30. Joinpoint graph of DTP3 in Saint Vincent and the Grenadines (2012-22).

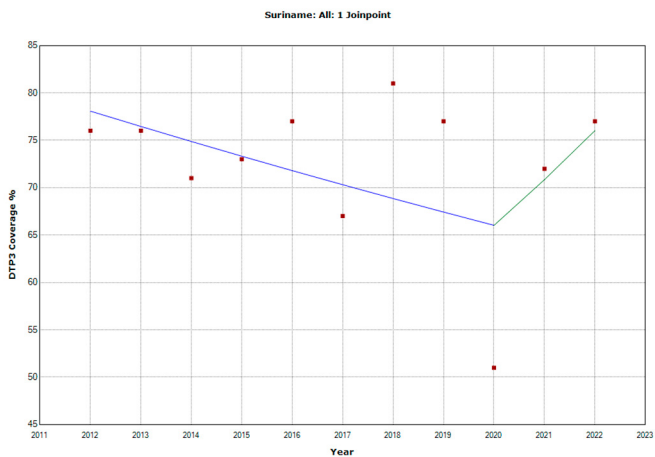


Figure 31. Joinpoint graph of DTP3 in Suriname (2012-22).

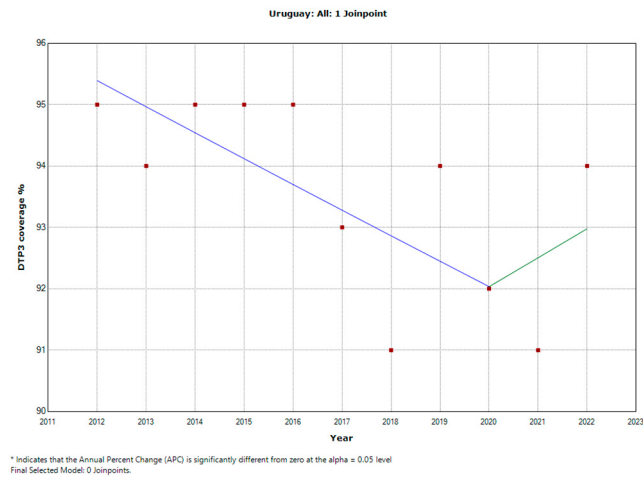


Figure 32. Joinpoint graph of DTP3 in Uruguay (2012-22).

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.

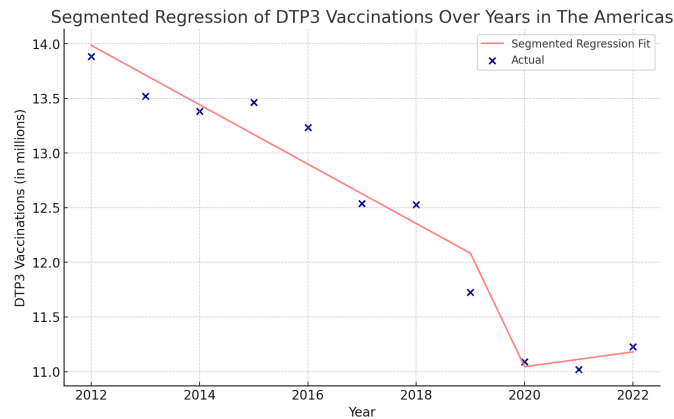


Figure 33. Segmented Regression Analysis of DTP3 in the Americas, representing the actual DTP3 vaccination numbers (in dark blue) against the predicted values from the segmented regression (in light coral).

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)

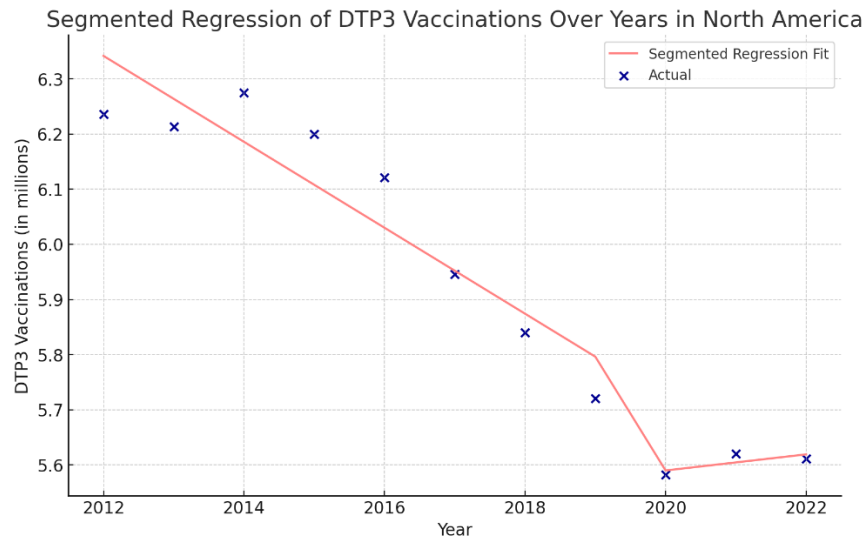


Figure 34. Segmented Regression Analysis of DTP3 in North America, representing the actual DTP3 vaccination numbers (in dark blue) against the predicted values from the segmented regression (in light coral).

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.

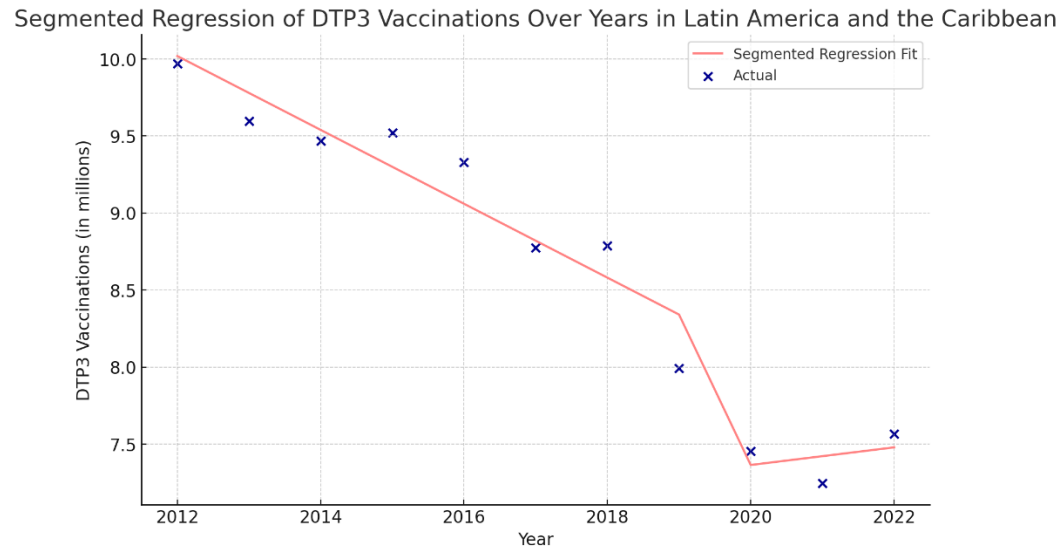


Figure 35. Segmented Regression Analysis of DTP3 Vaccination in Latin America and the Caribbean. The actual DTP3 vaccination numbers (in dark blue) against the predicted values from the segmented regression (in light coral).

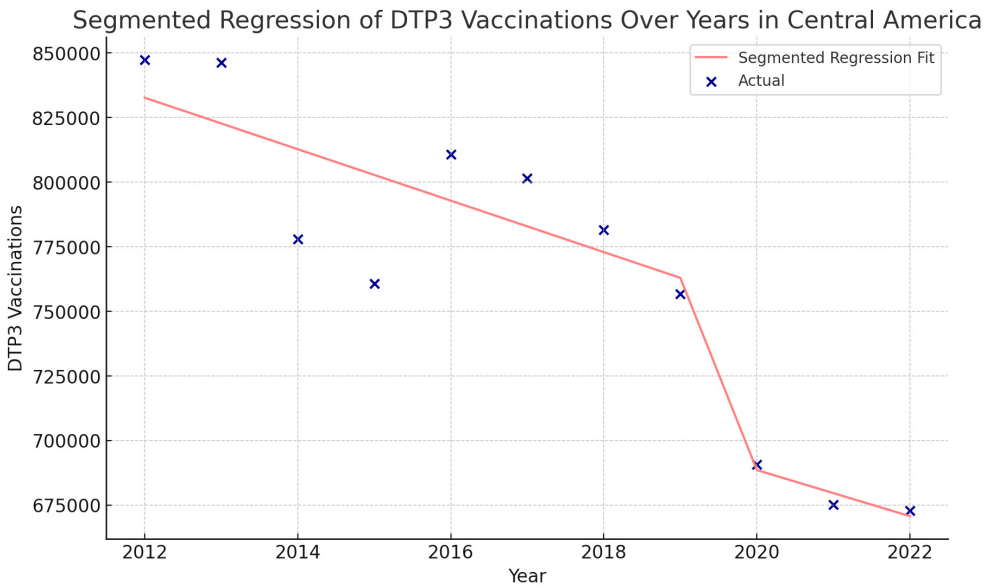


Figure 36. Segmented Regression Analysis of DTP3 vaccination in Central America. The actual DTP3 (in dark blue) against the predicted values from the segmented regression (in light coral).

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

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)

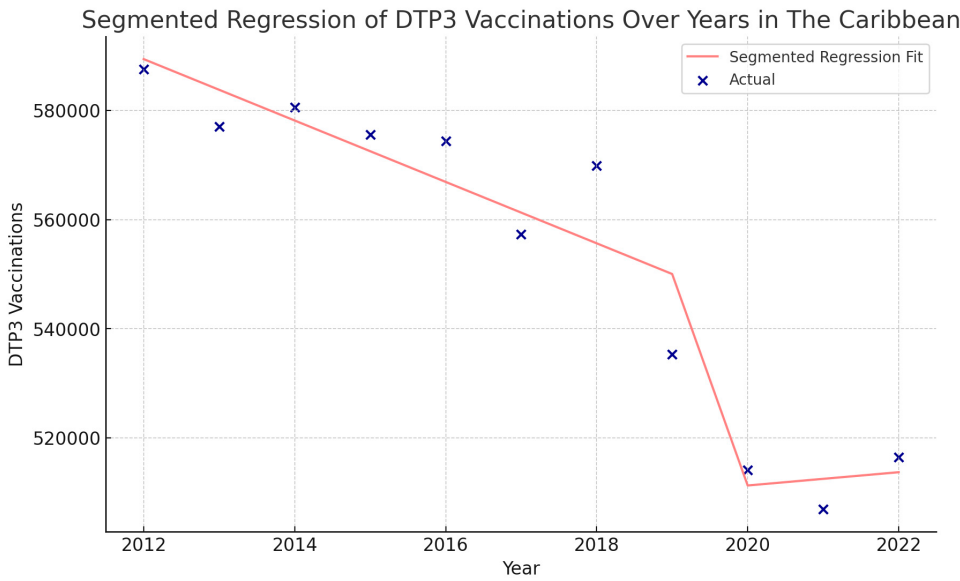


Figure 37. Segmented Regression Analysis of DTP3 Vaccination in the Caribbean. The actual DTP3 (in dark blue) against the predicted values from the segmented regression (in light coral).

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

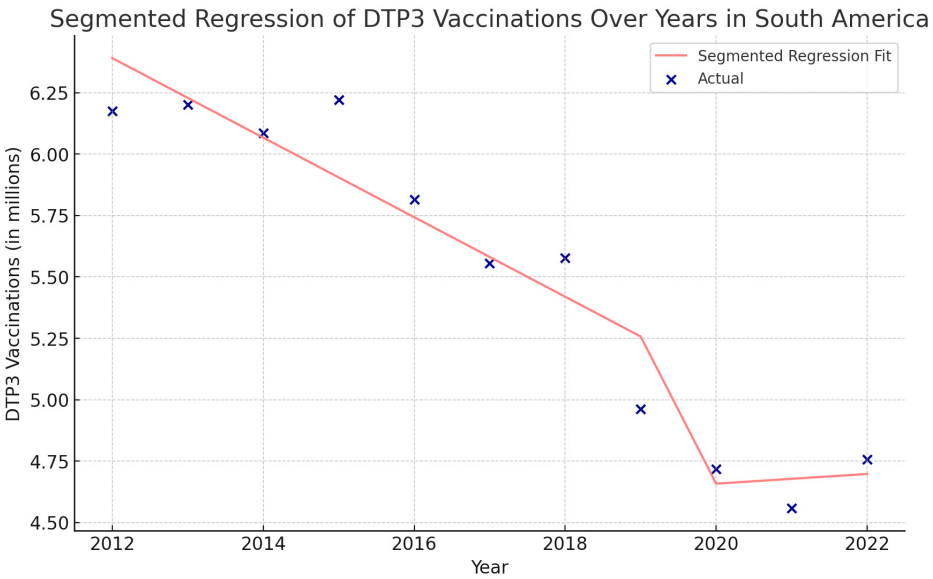


Figure 38. Segmented Regression Analysis of DTP3 Vaccination in South America. The actual DTP3 numbers (in dark blue) are represented against the predicted values from the segmented regression (in light coral).

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 signification. 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.

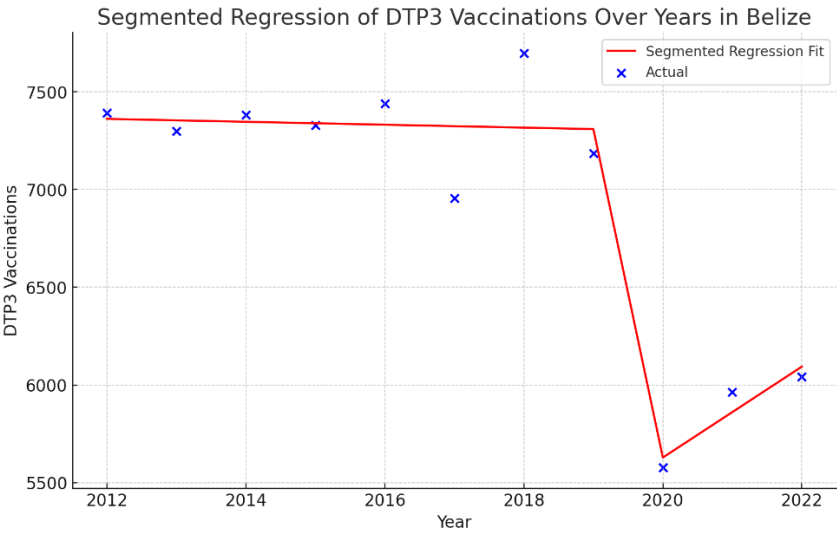


Figure 39. Segmented Regression Analysis of DTP3 Vaccination in Belize, representing the actual number of DTP3 vaccinations (in blue) and the fitted values from the segmented regression (in red).

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.

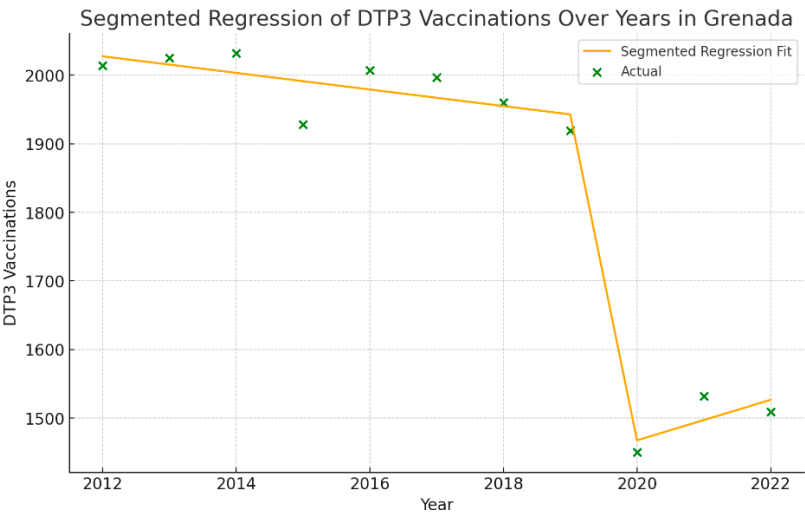


Figure 40. Segmented Regression Analysis of DTP3 vaccinations in Grenada represents the number of DTP3 vaccinations (in green) and the fitted values from the segmented regression (in orange).

The model for Peru (Figure 41) has an R^2 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.

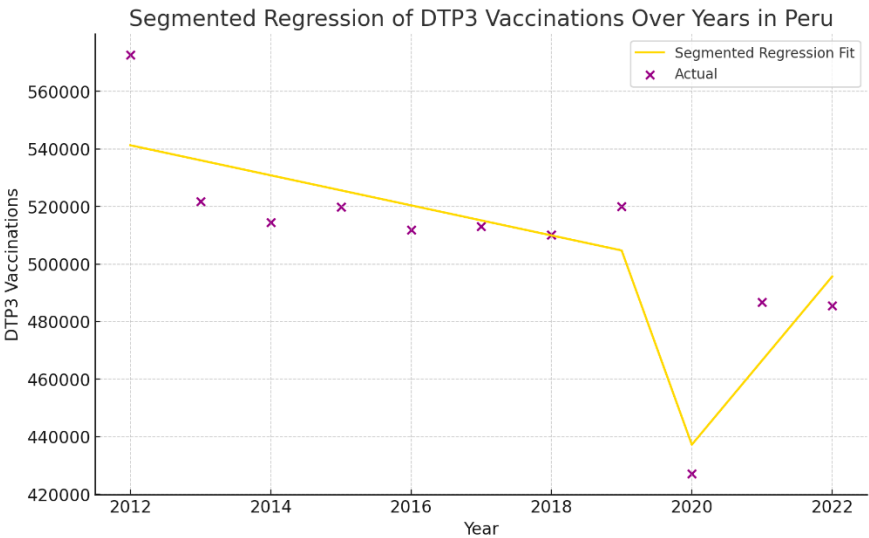


Figure 41. Segmented Regression Analysis of DTP3 vaccinations in Peru representing the actual DTP3 vaccination numbers (in purple) and the fitted values from the segmented regression (in gold),.

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.

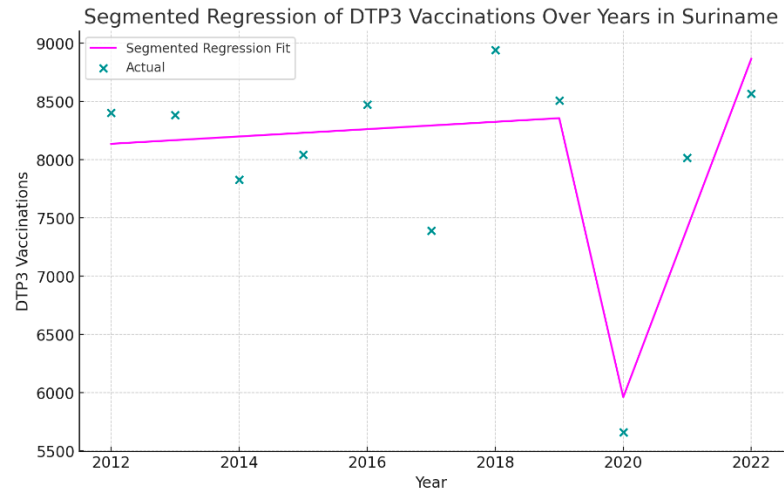


Figure 42. Segmented Regression Analysis of DTP3 vaccinations in Suriname representing the actual DTP3 vaccination numbers (in dark cyan) and the fitted values from the segmented regression (in magenta).

In Mexico (Figure 43), the model has a good fit with an R2 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 Covid19 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 ($p = 0.098$).

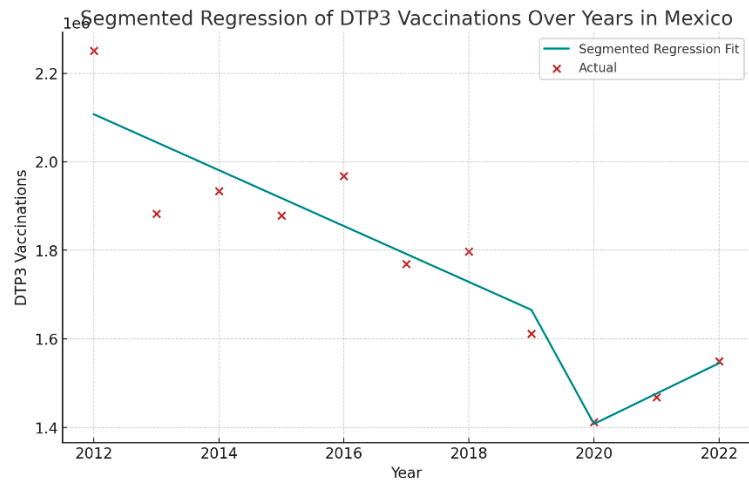


Figure 43. Segmented Regression Analysis of DTP3 vaccinations in Mexico representing the actual DTP3 vaccination numbers in (in brown) and the predicted values from the segmented regression (in teal).

The segmented regression analysis for the United States data (Figure 44) provides the following insights: the model has a good fit with an R2 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

point year and the occurrence of COVID-19 on the number of vaccinations, but it is also not statistically significant ($p = 0.099$).

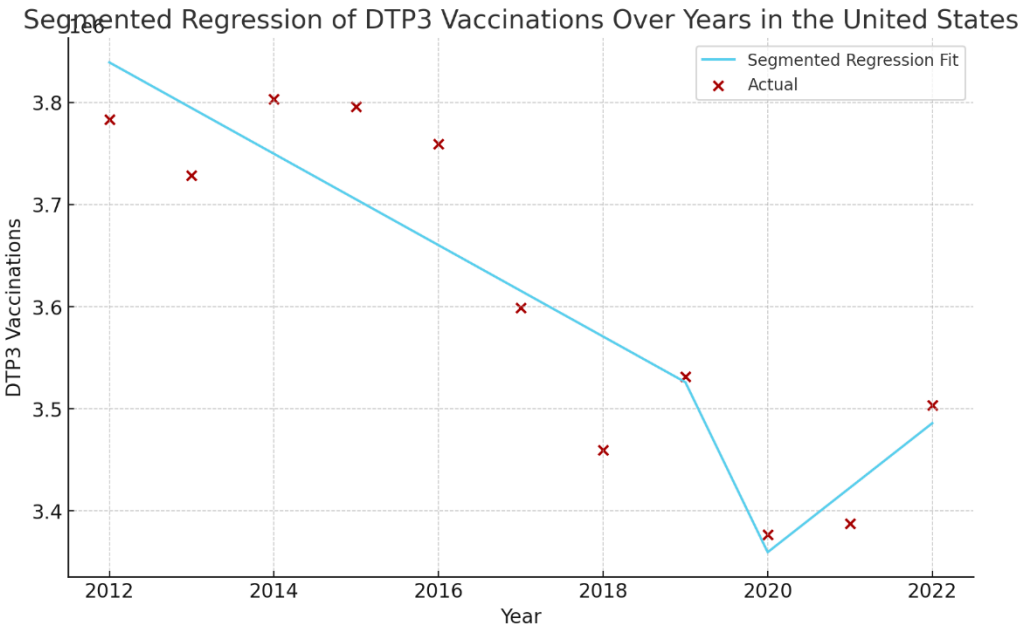


Figure 44. Segmented Regression Analysis of DTP3 vaccinations in the United States representing the actual DTP3 vaccination numbers in (in dark red) against the predicted values from the segmented regression (in sky blue).

Table 8 summarizes all the significant tests to allow for a global vision.

Table 8. Summary Table Displaying Joinpoints close to 2020, along with significant Chi-Square Test and Segmented Regression Analysis.

Country	Joinpoint			X ² 2019-22	Segmented regression 2002-22
	Estimate	Lower 95%CI	Upper 95%CI		
Antigua and Barbuda	2017	2014	2020	<0.001	
Argentina				<0.001	
Bahamas	2020	2014	2020		
Barbados					
Belize	2019	2014	2020	0.003	<0.05
Bolivia (Plurinational State of)				<0.001	
Brazil				<0.001	
Canada	2018	2016	2020		<0.05
Chile					
Colombia	2019	2017	2020	<0.001	
Costa Rica	2017	2014	2020		
Cuba					
Dominica	2020	2014	2020		
Dominican Republic					
Ecuador	2018	2014	2020	<0.001	
El Salvador				<0.001	
Grenada	2018	2014	2020		<0.05
Guatemala				<0.001	
Guyana					

Haiti	2017	2014	2020		
Honduras				<0.001	
Jamaica	2019	2014	2020		
Mexico	2020	2014	2020	<0.001	
Nicaragua	2018	2016	2020	<0.001	
Panama					
Paraguay	2018	2016	2019	<0.001	
Peru	2017	2014	2020	<0.001	<0.05
Saint Kitts and Nevis	2020	2014	2020		
Saint Lucia	2019	2014	2020		
Saint Vincent and the Grenadines	2017	2014	2020		
Suriname	2020	2014	2020		<0.05
Trinidad and Tobago					
Uruguay	2020	2014	2020		
United States					
Venezuela				<0.001	

4. Discussion

Our research focused on examining the effects of the COVID-19 pandemic on DTP immunization patterns across the Americas. Findings reveal that vaccination rates have been negatively impacted in various American countries, particularly 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 the United Nations Children’s Fund’s dataset for this investigation remains paramount. Despite the United Nations Children’s Fund’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 [71]. 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 appears to be a disparity between the number of countries in the Americas that experienced a significant drop in immunization rates between 2019 and 2022, totaling 22, and the smaller subset of 16 countries within this group where a decrease in vaccination trends was observed. This variation can be attributed to the fact that, despite the reduction in vaccine coverage in particular countries over the observed years, the decrease is not yet significant enough to establish a trend shift in some of these nations due to the small number of births in some countries. Additionally, the discrepancy in results between Joinpoint and segmented regression may also be influenced by the methodologies employed: Joinpoint regression identifies year-significant trend changes but with a

95% confidence interval that spans a range of years, whereas segmented regression focuses on a precise time point. This difference in approach to determining trend changes at specific times versus a range of years can lead to varying interpretations in the vaccination coverage data [72–74].

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 [75,76].

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.

Our analysis revealed that DTP3 rates remained constant throughout the 2019–22 pandemic in most North American nations, as shown in Table 4. This finding is intriguing and merits further investigation, especially considering the contrasting 4% absolute reduction in DTP3 rates observed across the Americas during the same timeframe. In this period, Canada and Mexico exhibited a minor increase in DTP3 rates, whereas the United States maintained its existing level of coverage.[4]. The countries that did not have their coverage affected at the end of the pandemic were Cuba, the United States of America, Trinidad and Tobago, Haiti, Chile, Uruguay, Costa Rica, and Suriname. These results could indicate the efficiency of the national vaccination programs and the resilience of healthcare systems in these countries, enabling them to sustain their immunization rates in the face of numerous challenges presented by the persistent COVID-19 pandemic globally.

Nevertheless, there are differences in subnational units. For example, In Haiti, a significant decrease in DTP3 service volume, amounting to 5% or more, was observed in 80% of the subnational regions during the third quarter of 2022.[77].

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 reduction might be ascribed to enduring issues in the country's health system infrastructure, particularly shortcomings in the vaccine distribution network, a situation potentially aggravated by the extra burden imposed by the COVID-19 pandemic [78–83].

Our study has revealed notable reductions in immunization rates across various American nations. Additionally, we observed a shift in the trend of vaccine coverage in Latin America and the

Caribbean. This trend shift, marked by an accelerated decline in coverage, was evident in all subregions. It proved statistically significant in the Caribbean ($P=0.031$) and South America ($P=0.001$). There was also a noticeable acceleration in the decline of coverage in Central America, although this has not yet reached statistical significance, possibly due to the limited duration of the follow-up period. Our findings are consistent with literature indicating that DTP3 rates witnessed a decline of -5.06% in the Caribbean and Latin America between 2019 and 2021. The DTP3 rate fell 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 [75]. The worldwide coverage of DTP3 experienced a decline of 5.81% from 2019 to 2021, decreasing from 86% to 81% [51]. 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 [51,84]. Similar declines had been found in Africa and Asia [44,85]. 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.

Numerous elements could account for the shift in vaccination coverage. Factors at the national level, like elevated fertility rates, combined with community-specific factors, such as widespread illiteracy, play a role in the higher incidence of unvaccinated children [33,86]. Research conducted in the US 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 [87].

In Africa, incomplete vaccinations are primarily due to caregivers' time constraints, limited immunization knowledge, vaccine or staff shortages at health facilities, missed vaccination chances, concerns about side effects, poor access to services, and caregiver vaccination beliefs [88]. A recent study shows that 35.5% of African populations have incomplete immunization, with home births,

rural residency, lack of prenatal care, limited immunization awareness, and maternal illiteracy being the main risk factors [89].

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 reductions emphasize the significant influence of the COVID-19 pandemic on regular vaccination programs within the Americas, signaling a need for focused efforts to recover and enhance vaccine coverage. Covid-19 had an impact on children's vaccination. The decline in vaccination rates can be linked to various factors associated with the COVID-19 pandemic, including the reallocation of healthcare resources to address the outbreak, the implementation of lockdowns, and the imposition of restrictions on movement that impeded access to vaccination services [90–93]. In a survey carried out among parents of children aged 0–4 years across America, Europe, and Australia, 83% of respondents considered it crucial for their child to receive the recommended vaccines despite the COVID-19 pandemic. About half of the routine vaccine appointments were postponed or canceled due to the pandemic. However, 61% of the parents indicated their desire to make up for missed vaccinations once COVID-19 restrictions were eased or lifted [94].

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 essential to highlight the situation in Brazil, where the DPT3 rate increased by 7% towards the conclusion of the COVID-19 pandemic. This rise could be credited to successful immunization strategies, focused interventions, or heightened governmental backing for vaccination initiatives during the crisis. Analyzing and drawing lessons from the experiences of these nations is essential for enhancing immunization services in 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 [95].

The disparities observed across different countries emphasize the importance of developing specific strategies to boost vaccination rates, particularly in nations experiencing a downturn in these trends. Persistent oversight of vaccination initiatives, addressing challenges within healthcare systems, and active community involvement is crucial for sustaining and improving immunization rates in these areas.

Our findings are consistent with previous studies showing that the worldwide COVID-19 pandemic has interrupted crucial health services, including vaccination efforts, and has been linked to growing inequities [96–98]. Moreover, concerns about contracting the virus and vaccine hesitancy might have contributed to parents' hesitancy in seeking healthcare facilities for their children's vaccinations [99,100]. 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 [14,101].

4.6. The Role of Healthcare Systems and Planning

The disruption caused by the COVID-19 pandemic has underscored the importance of having robust health systems capable of maintaining vital medical services during challenging times. [102]. Research has shown statistically significant differences in monthly vaccination rates between rural and urban regions [103]. The differences in vaccination trends across regions emphasize the necessity for customized public health approaches, called precision public health [103,104]. Policies must be region-specific, considering each area's unique challenges and resources.

Initiatives must be undertaken to fortify immunization programs and enhance vaccine coverage throughout the continent, especially in areas most impacted by the decline in vaccination rates.[105]. 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 decline in vaccination coverage has profound implications, such as the potential for outbreaks of diseases like diphtheria, tetanus, and pertussis, further straining healthcare systems amid the COVID-19 pandemic. Addressing the fall in immunization rates is critical, as the risks of postponing vaccinations are more significant than those associated with COVID-19 during routine immunizations [106].

Efforts to enhance immunization rates must consider factors like healthcare access, vaccine supply issues, and government commitment. The decrease in countries meeting WHO's DTP targets, particularly in Latin America and the Caribbean, underscores the need for targeted interventions. Additionally, even with improved vaccination programs, the time required for catch-up immunizations could be extended, raising the risk of disease outbreaks.[107,108]. Prompt and efficient vaccine distribution and recovery of coverage levels are essential. Collaboration among governments, healthcare bodies, and international agencies is crucial to preserve vaccination progress and protect populations from vaccine-preventable diseases [109–112]. [112] 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 [113]. It is crucial to monitor subnational units to avoid inequities [77].

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.

Author Contributions: Conceptualization, FGG, EAO, ERV and IAO; methodology, SGA, LGA, EAO ERV; software, SGA, LGA; investigation, RAB, EAO, ERV.; writing—original draft preparation, FGG, SGA, LGA, EAO, IAO, RAB ERV; writing—review and editing, FGG, SGA, LGA, IAO, EAO, RAB ERV; visualization, SGA, LGA; supervision, FGG, IAO. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Institutional Review Board Statement: This is not applicable because the study was done with publicly available databases.

Informed Consent Statement: Not applicable because the study was done with public available database.

Data Availability Statement: Data are available from the United Nations Children’s Fund database.

Conflicts of Interest: The authors declare no conflict of interest.

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.; Guttmann, 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.; Widiartari, 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>.

13. 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>.
14. 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>.
15. 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>.
16. 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>.
17. 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.
18. Yang, J.; Vaghela, S.; Yarnoff, B.; De Boissvilliers, 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>.
19. Chen, X.; Huang, H.; Ju, J.; Sun, R.; Zhang, J. Impact of Vaccination on the COVID-19 Pandemic in US States. *Sci Rep* 2022, 12 (1), 1554. <https://doi.org/10.1038/s41598-022-05498-z>.
20. 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.; Randriamamonjiarison, A. N.; Volahasina, T. A.; Rasoanaivo, F.; Rakotoarimanana, F. M. J.;

- Raheliari-vao, 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. Barbosa, J. Vaccination Week in the Americas Press Conference - Dr. Jarbas Barbosa, PAHO's Director Remarks - 20 April 2023 - PAHO/WHO | Pan American Health Organization <https://www.paho.org/en/documents/vaccination-week-americas-press-conference-dr-jarbas-barbosa-pahos-director-remarks-20> (accessed 2023 -12 -15).
 39. PAHO. Fact Sheet - Vaccination Week in the Americas 2023 - PAHO/WHO | Pan American Health Organization <https://www.paho.org/en/documents/fact-sheet-vaccination-week-americas-2023> (accessed 2023 -12 -15).
 40. PAHO. Risk of vaccine-preventable disease outbreaks at 30-year high, PAHO Director says <https://www.paho.org/en/news/20-4-2023-risk-vaccine-preventable-disease-outbreaks-30-year-high-paho-director-says> (accessed 2023 -12 -15).
 41. WHO/UNICEF. Progress and Challenges with Achieving Universal Immunization Coverage. 2022 WHO/UNICEF Estimates of National Immunization Coverage (WUENIC); Geneva, 2023.
 42. 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>.
 43. Shet, A.; Carr, K.; Danovaro-Holliday, M. C.; Sodha, S. V.; Prosperi, 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).
 44. Aguinaga-Ontoso, I.; Guillen-Aguinaga, S.; Guillen-Aguinaga, L.; Alas-Brun, R.; Onambebe, 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>.
 45. 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>.
 46. 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>.

47. THE GLOBAL HEALTH OBSERVATORY. Immunization and vaccine-preventable communicable diseases Immunization and vaccine-preventable communicable diseases (accessed 2023 -11 -29).
48. 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>.
49. World Health Assembly. Immunization Agenda 2030: A Global Strategy to Leave No One Behind.; WHO: Geneva, 2020.
50. UNICEF. COVID-19 pandemic fuels largest continued backslide in vaccinations in three decades <https://www.unicef.org/press-releases/WUENIC2022release> (accessed 2023 -05 -16).
51. 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).
52. 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).
53. World Bank. Population, total | Data <https://data.worldbank.org/indicator/SP.POP.TOTL> (accessed 2023 -05 -21).
54. 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>.
55. 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>.
56. 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>.
57. 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>.
58. Joinpoint Regression Program. Version 4.3.1.0. April, 2016; Statistical Methodology and Applications Branch, Surveillance Research Program, National Cancer Institute.
59. 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).
60. 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 Model-ing* 2014, 14 (4), 293–313. <https://doi.org/10.1177/1471082X13504721>.
61. 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>.
62. 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>.
63. 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>.
64. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna, Austria. 2023.
65. RStudio Team. RStudio: Integrated Development for R. RStudio, PBC.; Boston, MA. 2023.
66. Wickham, H. Ggplot2: Elegant Graphics for Data Analysis; Springer-Verlag: New York, 2016.
67. Wickham, H.; Bryan, J. Readxl: Read Excel Files_. R Package Version 1.4.3. 2023.
68. Mapchart Version 4.3.2. Mapchart. November 30, 2023.
69. 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>.
70. Brewer, C. A.; Hatchard, G. W.; Harrower, M. A. COLORBREWER 2.0 Color Advice for Cartograph. 2013.
71. 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>.

72. Maciak, M.; Mizera, I. Regularization Techniques in Joinpoint Regression. *Statistical Papers* 2016, 57 (4), 939–955. <https://doi.org/10.1007/s00362-016-0823-2>.
73. Kontopantelis, E.; Doran, T.; Springate, D. A.; Buchan, I.; Reeves, D. Regression Based Quasi-Experimental Approach When Randomisation Is Not an Option: Interrupted Time Series Analysis. *BMJ* 2015, 350 (jun09 5), h2750–h2750. <https://doi.org/10.1136/bmj.h2750>.
74. Taljaard, M.; McKenzie, J. E.; Ramsay, C. R.; Grimshaw, J. M. The Use of Segmented Regression in Analysing Interrupted Time Series Studies: An Example in Pre-Hospital Ambulance Care. *Implementation Science* 2014, 9 (1), 77. <https://doi.org/10.1186/1748-5908-9-77>.
75. 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>.
76. Urueña, A.; Machado, R.; Cunha, J.; López Colmano, C.; Rancano, C.; Kfour, 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>.
77. 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>.
78. United Nations. Global disparity in access to essential vaccines, says WHO report | UN News <https://news.un.org/en/story/2022/11/1130402> (accessed 2023 -12 -17).
79. WHO. Vaccine inequity undermining global economic recovery <https://www.who.int/news/item/22-07-2021-vaccine-inequity-undermining-global-economic-recovery> (ac-cessed 2023 -12 -17).
80. WHO. Global Vaccine Market Report 2022 <https://www.who.int/publications/m/item/global-vaccine-market-report-2022> (accessed 2023 -12 -17).
81. Guglielmi, G. Pandemic Drives Largest Drop in Childhood Vaccinations in 30 Years. *Nature* 2022, 608 (7922), 253. <https://doi.org/10.1038/D41586-022-02051-W>.
82. OECD. Access to COVID-19 vaccines: Global approaches in a global crisis - OECD https://read.oecd-ilibrary.org/view/?ref=1069_1069384-ewmqw9sx2&title=Access-to-COVID-19-vaccines-Global-approaches-in-a-global-crisis (accessed 2023 -12 -17).
83. Handfield R. Challenges and Opportunities to Expand the COVID-19 Vaccine Supply Chain: A Global Sum-mit | Supply Chain Resource Cooperative <https://scm.ncsu.edu/scm-articles/article/challenges-and-opportunities-to-expand-the-covid19-vaccine-supply-chain-a-global-summit> (accessed 2023 -12 -17).
84. 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>.
85. Evans, B.; Keiser, O.; Kaiser, L.; Jombart, T. Analysis of Global Routine Immunisation Coverage Shows Dis-ruption 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>.
86. Rachlin, A.; Carolina Danovaro-Holliday, M.; Murphy, P.; Samir, Sodha, V.; Wallace, A. S. Report Routine Vaccination Coverage-Worldwide, 2021. *Morbidity and Mortality Weekly* 2021, 71 (44), 1396–1400.
87. LaMori, J.; Feng, X.; Pericone, C. D.; Mesa-Frias, M.; Sogbetun, O.; Kulczycki, A. Hepatitis Vaccination Ad-herence and Completion Rates and Factors Associated with Low Compliance: A Claims-Based Analysis of US Adults. *PLoS One* 2022, 17 (2), e0264062. <https://doi.org/10.1371/journal.pone.0264062>.
88. Périeres, L.; Séror, V.; Boyer, S.; Sokhna, C.; Peretti-Watel, P. Reasons given for Non-Vaccination and un-der-Vaccination of Children and Adolescents in Sub-Saharan Africa: A Systematic Review. *Hum Vaccin Im-munother* 2022, 18 (5). <https://doi.org/10.1080/21645515.2022.2076524>.
89. 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>.
90. Cdc. CDC Strategy for Global Response to COVID-19 (2020-2023). 2022.

91. Dayaratna K; Tyrrell P; Vanderplas A. A Comparative Analysis of Policy Approaches to COVID-19 Around the World, with Recommendations for US Lawmakers | The Heritage Foundation <https://www.heritage.org/public-health/report/comparative-analysis-policy-approaches-covid-19-around-the-world> (accessed 2023 -12 -17).
92. Bliss, K. E. Strengthening Routine Immunizations and Responding to Covid-19. Center at the Center for Strategic and International Studies: Washington, DC 2020.
93. de Albuquerque Veloso Machado, M.; Roberts, B.; Wong, B. L. H.; van Kessel, R.; Mossialos, E. The Relationship Between the COVID-19 Pandemic and Vaccine Hesitancy: A Scoping Review of Literature Until August 2021. *Front Public Health* 2021, 9. <https://doi.org/10.3389/fpubh.2021.747787>.
94. 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>.
95. 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>.
96. Spencer, N.; Markham, W.; Johnson, S.; Arpin, E.; Nathawad, R.; Gunnlaugsson, G.; Homaira, N.; Rubio, M. L. M.; Trujillo, C. J. The Impact of COVID-19 Pandemic on Inequity in Routine Childhood Vaccination Cover-age: A Systematic Review. *Vaccines (Basel)* 2022, 10 (7), 1013. <https://doi.org/10.3390/vaccines10071013>.
97. Ning, C.; Wang, H.; Wu, J.; Chen, Q.; Pei, H.; Gao, H. The COVID-19 Vaccination and Vaccine Inequity Worldwide: An Empirical Study Based on Global Data. *Int J Environ Res Public Health* 2022, 19 (9), 5267. <https://doi.org/10.3390/ijerph19095267>.
98. Sabbatucci, M.; Odone, A.; Signorelli, C.; Siddu, A.; Silenzi, A.; Maraglino, F. P.; Rezza, G. Childhood Immunisation Coverage during the COVID-19 Epidemic in Italy. *Vaccines (Basel)* 2022, 10 (1), 120. <https://doi.org/10.3390/vaccines10010120>.
99. Olusanya, O. A.; Bednarczyk, R. A.; Davis, R. L.; Shaban-Nejad, A. Addressing Parental Vaccine Hesitancy and Other Barriers to Childhood/Adolescent Vaccination Uptake During the Coronavirus (COVID-19) Pandemic. *Front Immunol* 2021, 12. <https://doi.org/10.3389/fimmu.2021.663074>.
100. Sallam, M. COVID-19 Vaccine Hesitancy Worldwide: A Concise Systematic Review of Vaccine Acceptance Rates. *Vaccines (Basel)* 2021, 9 (2), 160. <https://doi.org/10.3390/vaccines9020160>.
101. 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>.
102. 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).
103. Soorapanth, S.; Cheung, R.; Zhang, X.; Mokdad, A. H.; Mensah, G. A. Rural–Urban Differences in Vaccination and Hesitancy Rates and Trust: US COVID-19 Trends and Impact Survey on a Social Media Platform, May 2021–April 2022. *Am J Public Health* 2023, 113 (6), 680–688. <https://doi.org/10.2105/AJPH.2023.307274>.
104. Olstad, D. L.; McIntyre, L. Reconceptualising Precision Public Health. *BMJ Open* 2019, 9 (9), e030279. <https://doi.org/10.1136/bmjopen-2019-030279>.
105. 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).
106. 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>.
107. 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>.

108. 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>.
109. 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>.
110. 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 US Jurisdictions, March–September 2020. *MMWR Morb Mortal Wkly Rep* 2021, 70 (23), 840–845. <https://doi.org/10.15585/mmwr.mm7023a2>.
111. 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>.
112. 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).
113. 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>.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.