Updated characterization of poliovirus transmission in Pakistan and Afghanistan and the impacts of different outbreak response vaccine options

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Main point: Given the epidemiological situation in Pakistan and Afghanistan in late 2020, using trivalent oral poliovirus vaccine (tOPV) to respond to cases caused by serotype 1 and 2 polioviruses offers substantial benefits

ABSTRACT

Background: Pakistan and Afghanistan remain the only reservoirs of wild poliovirus transmission. Prior modeling suggested that before the COVID-19 pandemic, plans to stop the transmission of serotype 1 wild poliovirus (WPV1) and persistent serotype 2 circulating vaccine-derived poliovirus (cVDPV2) did not appear on track to succeed.

Methods: We updated an existing poliovirus transmission and Sabin-strain oral poliovirus vaccine (OPV) evolution model for Pakistan and Afghanistan to characterize the impacts of immunization disruptions and restrictions on human interactions (i.e., population mixing) due to the COVID-19 pandemic. We also consider different options for responding to outbreaks and for preventive supplementary immunization activities (SIAs).

Results: The modeling suggests that with some resumption of activities in the fall of 2020 to respond to cVDPV2 outbreaks and full resumption on January 1, 2021 of all polio immunization activities to pre-COVID-19 levels, Pakistan and Afghanistan would remain off-track for stopping all transmission through 2023 without improvements in quality.

Conclusions: Using trivalent OPV (tOPV) for SIAs instead of serotype 2 monovalent OPV (mOPV2) offers substantial benefits for ending the transmission of both WPV1 and cVDPV2, because tOPV increases population immunity for both serotypes 1 and 2 while requiring fewer SIA rounds, when effectively delivered in transmission areas.

Keywords: polio, eradication, dynamic modeling, outbreak response

1. Introduction

As of January 2021, Pakistan and Afghanistan remain the last remaining reservoirs of serotype 1 wild poliovirus (WPV1) transmission [1-3]. Notably, Pakistan and Afghanistan reported 22, 33, 176, and 140 cases caused by WPV1 for 2017, 2018, 2019, and 2020, respectively [4]. Continued WPV1 transmission in Pakistan and Afghanistan led the Global Polio Eradication Initiative (GPEI) to miss key objectives of its 2013-2018 Strategic Plan [5] (which a 2015 midterm review extended to 2019 [6]). The GPEI prioritized the introduction of inactivated poliovirus vaccine (IPV) into Pakistan and Afghanistan in 2015 with the expectation that adding IPV would help to accelerate WPV1 eradication [5]. Delays in eradication of WPV1 necessitated the release of a 2019-2023 GPEI Strategic Plan [7], and challenges associated with outbreaks of serotype 2 circulating vaccine-derived polioviruses (cVDPV2) led to the release of an addendum to the plan in 2020 [8]. In early 2020, the GPEI anticipated widespread availability of a serotype 2 novel OPV (nOPV2) and that nOPV2 would completely replace mOPV2 to respond to cVDPV2 outbreaks by February 2021 [8]. As of March 2021, field trials with nOPV2 have just begun, and its properties remain uncertain. Because of the co-circulation of WPV1 and cVDPV2, trivalent OPV (tOPV) became the preferred vaccine for SIAs in Pakistan and Afghanistan beginning in late 2020.

Multiple prior studies characterized Pakistan and Afghanistan poliovirus epidemiology [9-14] and used dynamic transmission modeling to explore strategies to accelerate WPV1 eradication and manage cVDPV2 risks [15-18]. The transmission modeling studies characterized Pakistan and Afghanistan as one epidemiological block, which included subpopulations of under-vaccinated individuals in each country that preferentially mix and could sustain indigenous transmission [15-18]. Modeling the complex history of the use of different formulations of oral poliovirus vaccine (OPV) and different OPV and IPV vaccination strategies demonstrated the importance of substantially increasing OPV coverage of supplementary immunization activities (SIAs) in under-vaccinated subpopulations above that obtained previously in order to stop WPV1 transmission [15]. Other studies showed: (1) the importance of using proactive strategies to increase population immunity [16]; (2) the nature of the different types of surveillance information with respect to characterizing confidence about the absence of transmission as a function of time with no cases or environmental detections reported [17]; and (3) the tradeoffs of some characteristics of the poliovirus surveillance system in Pakistan and Afghanistan [18]. One statistical analysis reported relatively little role of

acute flaccid paralysis (AFP) surveillance data on resource allocation decisions for Pakistan [19]. Several other statistical analyses characterized the sensitivity and role of environmental surveillance in Pakistan and Afghanistan [20-22].

Prior to the coronavirus disease 2019 (COVID-19) pandemic, building on prior dynamic transmission modeling [15, 16], we updated the transmission model to reflect the actual poliovirus vaccine use and epidemiology through early 2020 [23, 24]. These analyses demonstrated that efforts to stop WPV1 poliovirus transmission in Pakistan and Afghanistan remained off track. Other studies highlight a number of important root causes related to the chronic failure to vaccinate in Pakistan and Afghanistan, access issues in areas where SIAs are 'banned' in Afghanistan, and significant issues with vaccine acceptance in Pakistan [2, 3]. In 2019, Pakistan reported 22 cVDPV2 cases and this transmission continued in 2020 with a reported 135 cases in Pakistan and 305 cases in Afghanistan [25]. A review of the cVDPV2 epidemiology [26] highlighted the unknown source of the 2019 cVDPV2 emergence in Pakistan. Updated global modeling of cVDPV2 transmission and risks [27] emphasized that the widespread cVDPV2 transmission in 2019 and early 2020 increased the chances of needing to globally restart use of serotype 2 OPV (OPV2) in routine immunization (RI) in OPV-using countries [28]. Extensive efforts to monitor the quality of SIAs continue to show gaps, and poliovirus surveillance data, which now includes the detection of polioviruses in environmental samples, provide further evidence that Pakistan and Afghanistan are not on track to interrupt transmission [2, 3].

As of the end of 2020, we recognized the need for another global model update due to the reduced social interactions, population mixing, and polio vaccine coverage caused by national responses to the COVID-19 pandemic [29]. This motivated us to also update our modeling of Pakistan and Afghanistan to consider the impacts of disruptions caused by the COVID-19 pandemic.

2. Methods

We updated our deterministic, differential equation-based (DEB) poliovirus transmission

and OPV evolution Pakistan and Afghanistan model [15-18, 24] to include the epidemiological experience through 2020 and to account for disruptions that occurred due to COVID-19 [29]. Briefly, the model divides the population into eight immunity states for fully susceptible, maternally immune, and six partially immune states following live poliovirus infections (WPV and/or OPV),

and/or successful IPV vaccination [23, 24]. The model describes waning of immunity as a five-stage process, infection as a process with two latent and four infectious stages for both fecal-oral and oral-oral transmission, and OPV evolution as a 20-stage process (i.e., stage 0 for fully attenuated Sabin strains to stage 19 for fully reverted cVDPV strains) [23, 24].

The model divides the populations of each country into a general population and an under-vaccinated subpopulation. The under-vaccinated population represents a conceptual construct characterized primarily by historically low vaccination levels, rather than geography [15-18]. The model aggregates all under-vaccinated communities from different parts of Pakistan and Afghanistan and including mobile populations [15-18]. As previously estimated, we assume the under-vaccinated subpopulation represents 5% of the total population of Pakistan and 10% of the total population of Afghanistan [15-18]. The top of Table 1 summarizes general inputs for Pakistan and Afghanistan related to the model population structure, poliovirus transmission, and vaccination that remained constant in all model runs [15-18]. Consistent with historical epidemiological evidence, the model assumes a constant seasonal variation pattern for each country, although recent epidemiological data do not show the same temporal pattern. The bottom of Table 1 summarizes model inputs used to the characterize the COVID-19 disruptions (i.e., beginning and end time of restrictions, change in average R_0 and RI coverage) consistent with prior global modeling [29].

Based on the model behavior in relation to cVDPV2 transmission in Pakistan, and its spread to Afghanistan, we assumed that both under-vaccinated subpopulations remain isolated relative to the general population such that they continue to preferentially mix with themselves and each other (Table 2a). We intensify the isolation from 2017 due to temporary border closures [15-18], which complicated (but did not stop) the process of crossing the border (Table 2b). Starting on March 20, 2020, we assume a second intensification of isolation due to the restrictions related to COVID-19 pandemic (Table 2c) followed by a return to the pre-COVID-19 levels after relaxation of the restrictions that we assumed would occur on January 1, 2021 [29].

We updated the RI coverage information based on the recent estimates of the national coverage with 3 doses of diphtheria-tetanus-pertussis vaccine (DTP3) by country [30], and recent Demographic and Health Study (DHS) point estimates of poliovirus vaccine birth dose coverage

(POL0) and coverage for 1, 2, and 3 poliovirus vaccine doses (POL1, POL2, and POL3) [31], Figure 1 shows the updated assumed RI coverage by dose over time. We also updated the SIA history from 2017 through 2020, including gaps in the SIA schedule during the COVID-19 pandemic disruption. Figure 2 shows our assumptions for the historical SIAs for Pakistan and Afghanistan by type of vaccine used and the fraction of the population targeted (see Appendix for subpopulation-specific assumptions, which include assumptions about the fraction targeted multiplied by assumed true coverage and the round-to-round probability of repeatedly missing the same children).

Following the unexpected introduction of serotype 2 virus and subsequent cVDPV2 outbreak in Pakistan in 2019, we include 5 point introductions of OPV-related virus (at the model reversion stage 5 consistent with partially reverted virus) occurring 10 days apart in the first half of 2019 [24]. In response to the outbreak, Pakistan started using mOPV2 rounds from November 2019. We assume that some of the children in mobile populations that received mOPV2 in Pakistan cross the border into Afghanistan. We capture this in the model by introducing mOPV2 at the time of outbreak response SIAs in areas surrounding the border (with an assumed 1-day delay relative to the start day of the related mOPV2 SIA) to a small number of children ages 3 months to 4 years residing in Afghanistan. We assume that this spillover of mOPV2 continues until COVID-19 related restrictions led to more isolation between the two countries. For these introductions, we assumed a frequency of 2 fully susceptible children per age group per day received the mOPV2 prior to entering Afghanistan for the duration of the related mOPV2 SIA.

Given the substantial and widespread transmission of both WPV1 and cVDPV2 in Pakistan and Afghanistan in 2020, the GPEI and countries plan to use trivalent OPV (tOPV, containing all three OPV serotypes) for some SIAs instead of separate SIAs using serotype 2 monovalent OPV (mOPV2) and bivalent OPV (bOPV, containing serotypes 1 and 3 OPV). Table 3 shows the base case (BC) vaccination schedule assumed for both countries from October 2020 to December 2023 based on information available in October 2020, which includes the use of two tOPV rounds (October 2020 and January 2021) in both countries according to plans at that time, followed by the assumed use of bOPV for SIAs (and assuming the same estimates for true coverage and repeatedly missed probabilities [23]) for the remainder of the time horizon (through December 31, 2023). For the alternative scenarios we include: (i) “tOPV use 2021 only,” which maintains the same schedule as the BC except for substituting tOPV for two bOPV rounds (September and November of 2021) in the

under-vaccinated subpopulation of Pakistan with fraction targeted equal to 1.0 (i.e., covering entire under-vaccinated subpopulation), (ii) "tOPV use," which maintains the same schedule as BC until mid-2021 and substitutes some bOPV rounds with tOPV beginning in the second half of 2021 through 2023, (iii) "tOPV and mOPV2 use," which maintains the same schedule as BC until mid-2021 and substitutes mOPV2 for the same bOPV rounds as the "tOPV use" scenario beginning in the second half of 2021, and (iv) "mOPV2 use," which substitutes all tOPV rounds with mOPV2 until mid-2021 and substitutes the same bOPV rounds as the "tOPV use" scenario with mOPV2 beginning in the second half of 2021.

3. Results

Figure 3 compares the updated modeled paralytic incidence to reported poliovirus cases for 2016-2020 for Pakistan and Afghanistan for (a) serotype 1 and (b) serotype 2. The model closely estimates the total 2020 WPV1 paralytic incidence (i.e., for Pakistan 125 modeled compared to 84 confirmed cases, and for Afghanistan 56 modeled cases confirmed to 56 confirmed cases). The model underestimates cVDPV2 paralytic incidence (i.e., for Pakistan 71 modeled compared to 135 confirmed cases, and for Afghanistan 281 modeled cases confirmed to 305 confirmed cases). Given the reported use of vaccines prior to 2020, these results suggest some disconnect between the expected population immunity based on the model and the observed incidence of paralytic cases as a function of time.

Figure 4 compares the modeled paralytic incidence of "tOPV use 2021 only" (dotted lines), "tOPV use" (dashed lines), "tOPV and mOPV2 use" (dotted-dashed lines), and "mOPV2 use" (double-dotted-dashed lines) to the base case (solid lines) for 2019-2023 for Pakistan and Afghanistan for (a) serotype 1 and (b) serotype 2. The WPV1 paralytic incidence of "tOPV use 2021 only" and "tOPV use" for Pakistan closely approximate the base case, whereas the incidence of "tOPV and mOPV2 use" is considerably higher, and much higher still for "mOPV2 use." Figure 4 shows a similar, but less pronounced, incidence pattern for Afghanistan. Limited targeting of only the under-vaccinated subpopulation ("tOPV use 2021 only") when detecting cVDPV2 cases only serves to delay the outbreak occurring under the BC. Since the model assumes the same take rate for mOPV2 as for serotype 2 component of tOPV, all scenarios using serotype 2 containing vaccine throughout the time horizon (except "tOPV use 2021 only") in Figure 4 (b) give the same result (lines covering each

other), preventing most of the cVDPV2 cases suggested by the base case. However, the assumed two-round, high target response of serotype 2 containing antigen repeated in 2021, 2022, and 2023 in Pakistan, and 2022 and 2023 in Afghanistan are not enough to stop the transmission, given unchanged quality of these activities. While the choice of the vaccine does not influence the outcome for cVDPV2 and leads to 2,461 and 512 expected cases saved in Pakistan and Afghanistan, respectively, compared to the base case, it substantial increases WPV1 transmission and expected cases. Depending on the vaccine choice used to respond to cVDPV2 outbreaks, the model suggests an expected 45-438 and 3-68 more WPV1 cases in Pakistan and Afghanistan, respectively, compared to the base case, with the worst outcome observed for the "mOPV2 use" scenario (i.e., tOPV never reintroduced into those countries).

4. Discussion

Significant setbacks in Pakistan's polio eradication program began during 2018, with a sharp increase in WPV1 cases and the emergence of cVDPV2 cases in 2019 [2]. In Afghanistan, widespread bans on house-to-house vaccination in conflict areas since April 2018 resulted in increasing numbers of WPV1 cases, and the spread of the cVDPV2 Pakistan outbreak to Afghanistan in 2020 [3]. The outbreak cVDPV2 viruses spread beyond the outbreak areas and the use of mOPV2 in both Pakistan and Afghanistan led to the detection of some new cVDPV2 emergences in late 2020. Ongoing transmission of WPV1 and cVDPV2 in Pakistan and Afghanistan suggest the need for strategies that will improve the quality of campaigns and vaccine coverage. In this analysis, simply switching SIAs back to tOPV in Pakistan and Afghanistan instead of alternately using mOPV2 and bOPV substantially improves population immunity to transmission for serotype 1, but not enough to stop WPV1 transmission. Our assumptions may prove optimistic with respect to the coverage that SIAs will achieve since we assumed resumption of SIAs at pre-COVID-19 coverage levels starting in January 1, 2021. If programmatic activities do not recover this quickly or as much, then the expected cases will increase. We suggest future modeling efforts should continue to monitor the actual performance of polio immunization activities in Pakistan and Afghanistan. We did not consider the use of IPV for outbreak response since prior studies suggest its inferior impact (compared with OPV) with respect to both effectiveness and cost-effectiveness, and the SAGE recently recommended no IPV use for outbreak response.

The insights from this analysis are limited by our assumptions, the model structure, available information, and uncertainty about our reconstruction of the immunization histories and assumptions about future actions [23]. Notably, this modeling assumes unlimited supplies of vaccine, but real supplies of all OPV2 containing vaccines remain limited. For all of the modeled scenarios, we assume the same total number of OPV doses used, and only vary the vaccine choice related to the formulation of the OPV. Using this approach yields comparisons of scenarios that imply the same vaccine administration costs and similar vaccine purchase costs, such that we can focus only on the implications of vaccine choices for outbreak response on population immunity to transmission. We sought to explore the consequences of mobile under-vaccinated populations by allowing a small amount of secondary spread of OPV used for outbreak response in Pakistan to enter Afghanistan, but whether and how much of this occurs remains uncertain due to limited information. Our assumption of homogeneous mixing within subpopulations can imply rapid transmission across relatively large groups of individuals, although we include heterogeneous mixing between the subpopulations and using mixing matrices that limit the transmission to some degree. Our differential equation-based transmission and OPV evolution model reproduces average poliovirus transmission dynamics at the level of abstraction of the model, but does not capture population micro dynamics that impact die-out of transmission and re-introduction of transmission due to importation of cases. Notably, our model does not capture critical aspects of the stochastic nature of transmission events in real populations. The two under-vaccinated modeled subpopulations represent people with substantial time-varying heterogeneity in vaccine coverage, which our simplified model structure cannot fully reproduce.

With the resumption of tOPV use in Pakistan and Afghanistan and substantial transmission of cVDPV2 in Africa, resuming the use of tOPV in areas that need OPV2 in response to cVDPV2 transmission would likely offer the most cost-effective strategy to keep population immunity to all 3 serotypes higher. Given the challenges associated with delivering vaccine in the wake of COVID-19, this may help best to limit the transmission of cVDPV2 and help to prevent some cVDPV1 and cVDPV3 emergences in areas that otherwise would not receive bOPV SIAs. This analysis underscores the consequences of low SIA quality and reinforces the key findings of prior modeling, that Pakistan and Afghanistan will need to increase SIA quality to stop poliovirus transmission. Using tOPV will offer a tool to provide protection for all three serotypes with fewer total SIA rounds, but it will not compensate for continued poor performance or low immunization coverage.

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Declaration of interest

None.

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Figure captions (Figures provided separately)

Figure 1. Assumed routine immunization (RI) coverage by dose with oral poliovirus vaccine (OPV) for birth dose, one nonbirth dose, two nonbirth doses, and three or more nonbirth doses

(a) Pakistan, (b) Afghanistan

Figure 2. Historical supplementary immunization activities (SIAs) by type of vaccine used and fraction of the population targeted (a) Pakistan, (b) Afghanistan

Figure 3. Updated modeled paralytic incidence compared to reported poliovirus cases for 2016-2020 for Pakistan and Afghanistan (a) serotype 1, (b) serotype 2

Figure 4. Modeled paralytic incidence of the vaccination scenarios compared to a base case for 2019-2023 for Pakistan and Afghanistan (a) serotype 1, (b) serotype 2

Table 1. Inputs specific for the Pakistan and Afghanistan model

Model input	Best estimate	Notes and sources
General		
Number of subpopulations	4	[15-18]
Size of under-vaccinated subpopulations relative to total population: - Pakistan - Afghanistan	 0.05 0.10	[15-18]
Number of age groups	11	0-2, 3-11 months; 1; 2; 3; 4; 5-9; 10-14; 15-24; 25-39*; ≥ 40 years [15-18]
Number of mixing age groups	3	0–4; 5–14; ≥ 15 years [15-18]
Proportion of contacts reserved for individuals within the same mixing age group (κ)	0.35	Measure of strength of preferential mixing between age groups; value similar to other high-risk settings [15-18]
Average basic reproductive number (R_0) - serotype 1 - serotype 2 - serotype 3	 11 9.9 8.25	Seasonal variation occurs around the average, ratios by serotype based on generic model inputs [15-18]
Proportional change in R_0 due to seasonality (α)	0.15	Based on judgment and calibration within ranges used for other populations to match incidence pattern [15-18]
Day of seasonal peak in $R_{0(pd)}$ - Pakistan - Afghanistan	 180 (June 30) 240 (August 29)	Broadly consistent with typical precipitation patterns and nonpolio enterovirus isolation rates, calibrated to match incidence patterns [15-18]
Proportion of transmissions via oropharyngeal route (p^{oro})	0.3	Value used for high R_0 developing country settings [15-18]
Per-dose take rate (tr) (serotype 1, 2, 3) - tOPV - mOPV - bOPV - IPV	 0.40, 0.60, 0.52 0.52, 0.60, 0.52 0.48, NA, 0.48 0.63, 0.63, 0.63	Values based on review of seroconversion studies [15-18]
Time of IPV introduction in RI - Pakistan - Afghanistan	 August 20, 2015 September 30, 2015	[15-18]
Time of switch from tOPV to bOPV	April 30, 2016	[15-18]
Demographics	Time series	Surviving birth rates and age-specific mortality rates over time computed from U.N.-estimated medium variant annual number of surviving infants and population in each age group and country [15-18]
Transmission threshold	5/1,000,000	Effective infectious proportion below which we assume 0 force-of-infection [15-18]
Related to COVID-19		
Mixing restriction start date	March 20, 2020	

Mixing restriction end date	August 31, 2020	
Subpopulation-specific R_0 decrease during mixing restriction period	-1	
RI reduction start date	March 20, 2020	
RI reduction end date	December 31, 2020	
Change in average RI coverage during RI reduction period	-0.1	

Abbreviations: bOPV, bivalent oral poliovirus vaccine; COVID-19, coronavirus disease 2019, IPV, inactivated poliovirus vaccine; mOPV, monovalent oral poliovirus vaccine; NA, not applicable; RI, routine immunization; tOPV, trivalent oral poliovirus vaccine; U.N., United Nations.

Table 2. Assumed mixing matrices among the four subpopulations in the Pakistan and Afghanistan:

(a) Before intensification of border security (until and including 2016) [15-18]

To\From	Pakistan under-vaccinated	Pakistan general	Afghanistan under-vaccinated	Afghanistan general
Pakistan under-vaccinated	0.9970	0.0010	0.0015	0.0005
Pakistan general	0.0006	0.9990	0.0002	0.0002
Afghanistan under-vaccinated	0.0010	0.0005	0.9970	0.0015
Afghanistan general	0.0002	0.0002	0.0006	0.9990

(b) After intensification of border security (from January 1, 2017 to March 20, 2020) and once activities disrupted by COVID-19 resume (from September 1, 2020 through the December 31, 2023)

To\From	Pakistan under-vaccinated	Pakistan general	Afghanistan under-vaccinated	Afghanistan general
Pakistan under-vaccinated	0.9982	0.0010	0.0004	0.0004
Pakistan general	0.0006	0.9990	0.0002	0.0002
Afghanistan under-vaccinated	0.0004	0.0004	0.9977	0.0015
Afghanistan general	0.0002	0.0002	0.0006	0.9990

(c) During COVID-19 restrictions (from March 20, 2020 to August 31, 2020)

To\From	Pakistan under-vaccinated	Pakistan general	Afghanistan under-vaccinated	Afghanistan general
Pakistan under-vaccinated	0.9996	0.0002	0.0001	0.0001
Pakistan general	0.0002	0.9996	0.0001	0.0001
Afghanistan under-vaccinated	0.0001	0.0001	0.9996	0.0002
Afghanistan general	0.0001	0.0001	0.0002	0.9996

Table 3. Vaccination schedule for modeled scenarios in Pakistan and Afghanistan

Activity start date	Pakistan						Afghanistan					
	Target pop.	Vaccine					Target pop.	Vaccine				
		Base case	tOPV use 2021 only	tOPV use	tOPV and mOPV2	mOPV2 use		Base case	tOPV use 2021 only	tOPV use	tOPV and mOPV2	mOPV2 use
2020-10-26	7 % 77 %	mOPV2 tOPV	mOPV2 tOPV	mOPV2 tOPV	mOPV2 tOPV	mOPV2 mOPV2	55% 45%	bOPV tOPV	bOPV tOPV	bOPV tOPV	bOPV tOPV	bOPV mOPV2
2020-11-30	100 %	bOPV	bOPV	bOPV	bOPV	bOPV	55% 45%	bOPV tOPV	bOPV tOPV	bOPV tOPV	bOPV tOPV	bOPV mOPV2
2021-01-04	100 %	tOPV	tOPV	tOPV	tOPV	mOPV2	-	-	-	-	-	-
2021-01-15	-	-	-	-	-	-	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2021-02-15	100 %	bOPV	bOPV	bOPV	bOPV	bOPV	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2021-04-01	50 %	bOPV	bOPV	bOPV	bOPV	bOPV	50 %	bOPV	bOPV	bOPV	bOPV	bOPV
2021-05-15	50 %	bOPV	bOPV	bOPV	bOPV	bOPV	50 %	bOPV	bOPV	bOPV	bOPV	bOPV
2021-09-15	50 %	bOPV	tOPV* bOPV	tOPV	mOPV2	mOPV2	50 %	bOPV	bOPV	bOPV	bOPV	bOPV
2021-11-15	100 %	bOPV	tOPV* bOPV	tOPV	mOPV2	mOPV2	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2021-12-15	100 %	bOPV	bOPV	bOPV	bOPV	bOPV	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2022-01-15	100 %	bOPV	bOPV	bOPV	bOPV	bOPV	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2022-02-15	100 %	bOPV	bOPV	bOPV	bOPV	bOPV	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2022-03-15	50 %	bOPV	bOPV	bOPV	bOPV	bOPV	50 %	bOPV	bOPV	tOPV	mOPV2	mOPV2
2022-05-15	50 %	bOPV	bOPV	bOPV	bOPV	bOPV	50 %	bOPV	bOPV	tOPV	mOPV2	mOPV2
2022-09-15	50 %	bOPV	bOPV	tOPV	mOPV2	mOPV2	50 %	bOPV	bOPV	bOPV	bOPV	bOPV
2022-11-15	100 %	bOPV	bOPV	tOPV	mOPV2	mOPV2	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2022-12-15	100 %	bOPV	bOPV	bOPV	bOPV	bOPV	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2023-01-15	100 %	bOPV	bOPV	bOPV	bOPV	bOPV	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2023-02-15	100 %	bOPV	bOPV	bOPV	bOPV	bOPV	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2023-03-15	50 %	bOPV	bOPV	bOPV	bOPV	bOPV	50 %	bOPV	bOPV	tOPV	mOPV2	mOPV2
2023-05-15	50 %	bOPV	bOPV	bOPV	bOPV	bOPV	50 %	bOPV	bOPV	tOPV	mOPV2	mOPV2
2023-09-15	50 %	bOPV	bOPV	tOPV	mOPV2	mOPV2	50 %	bOPV	bOPV	bOPV	bOPV	bOPV
2023-11-15	100 %	bOPV	bOPV	tOPV	mOPV2	mOPV2	100 %	bOPV	bOPV	bOPV	bOPV	bOPV
2023-12-15	100 %	bOPV	bOPV	bOPV	bOPV	bOPV	100 %	bOPV	bOPV	bOPV	bOPV	bOPV

Notes: * tOPV use only in under-vaccinated subpopulation targeting 100% of under-vaccinated subpopulation

Abbreviations: bOPV, bivalent OPV; mOPV2, monovalent OPV serotype 2; OPV, oral poliovirus vaccine; tOPV, trivalent OPV.

Figure 1a

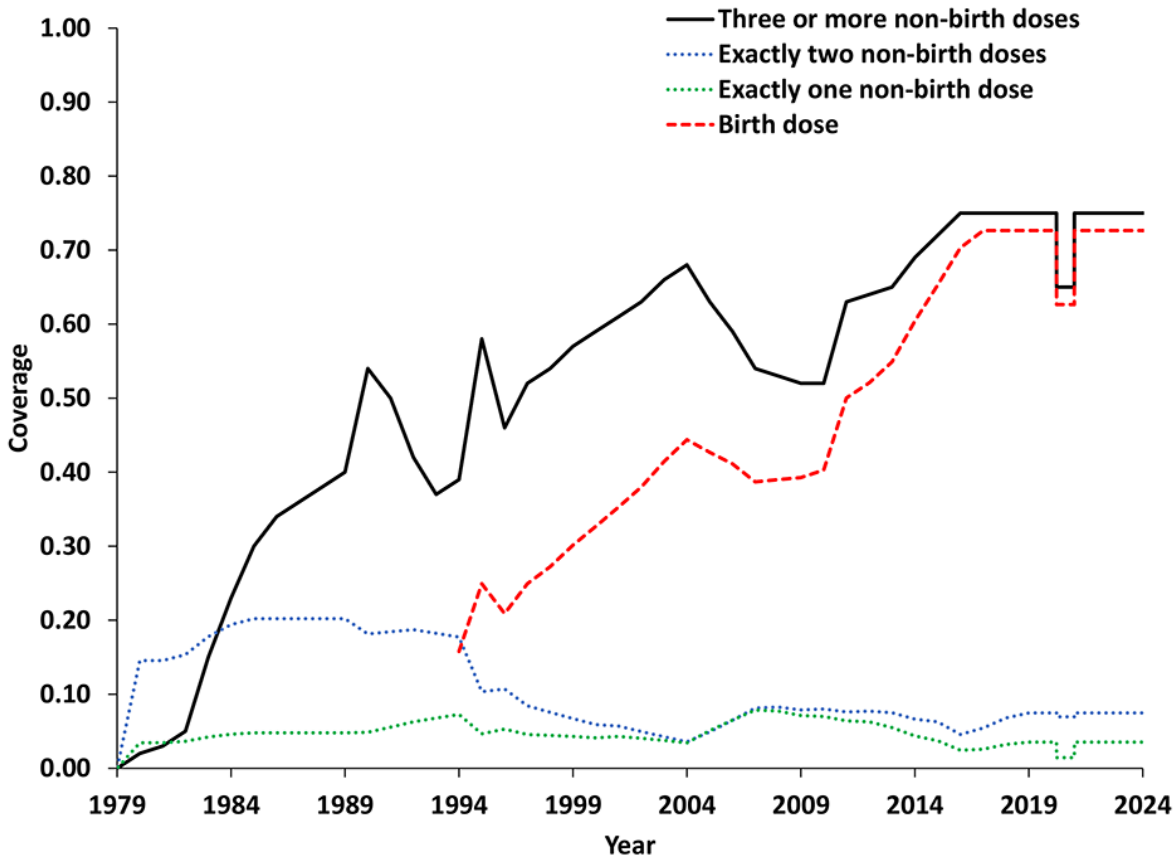

Three or more non-birth doses
Exactly two non-birth doses
Exactly one non-birth dose
Birth dose
Coverage
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1979
1984
1989
1994
1999
2004
2009
2014
2019
2024
Year

Figure 1b

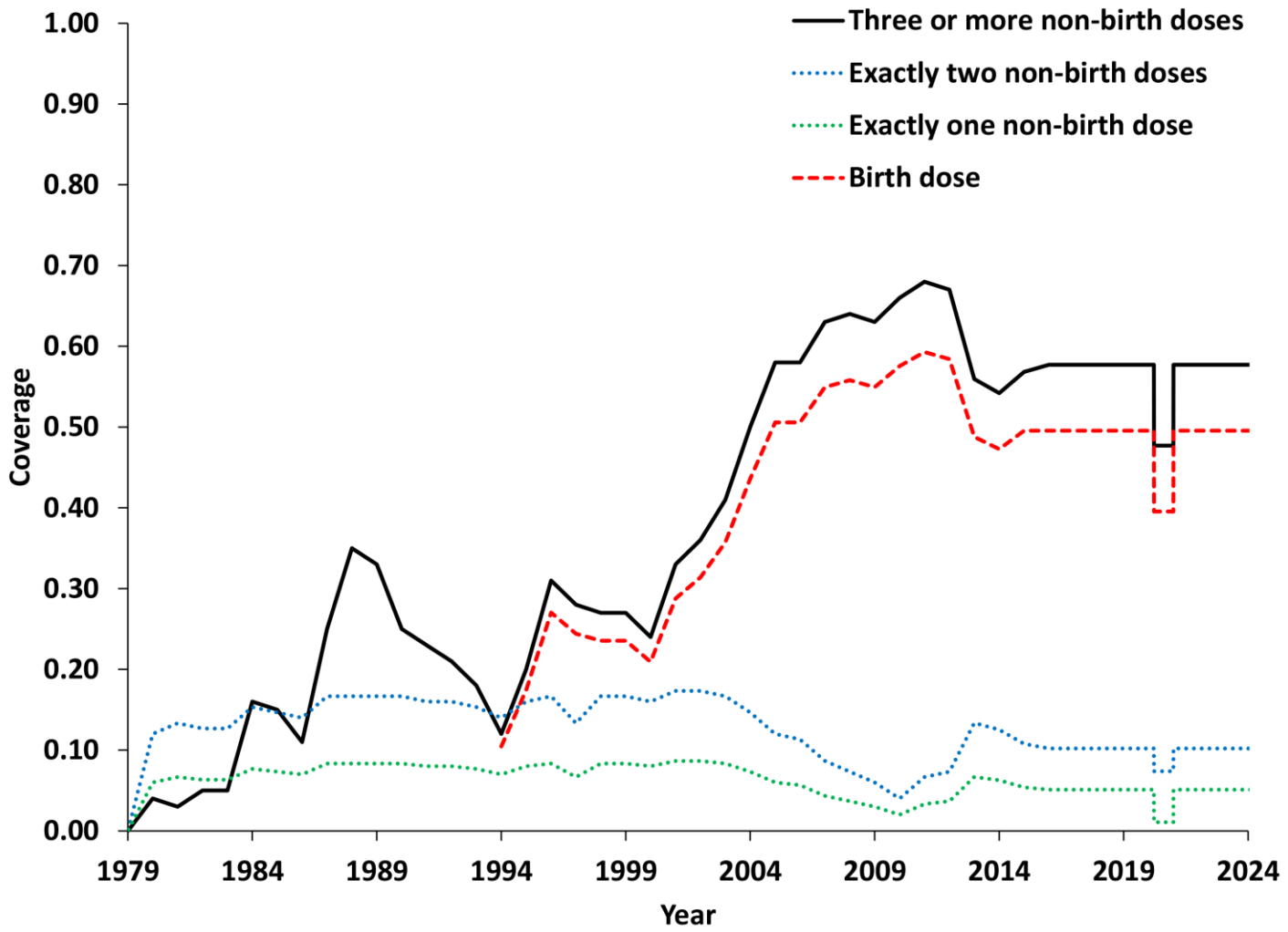
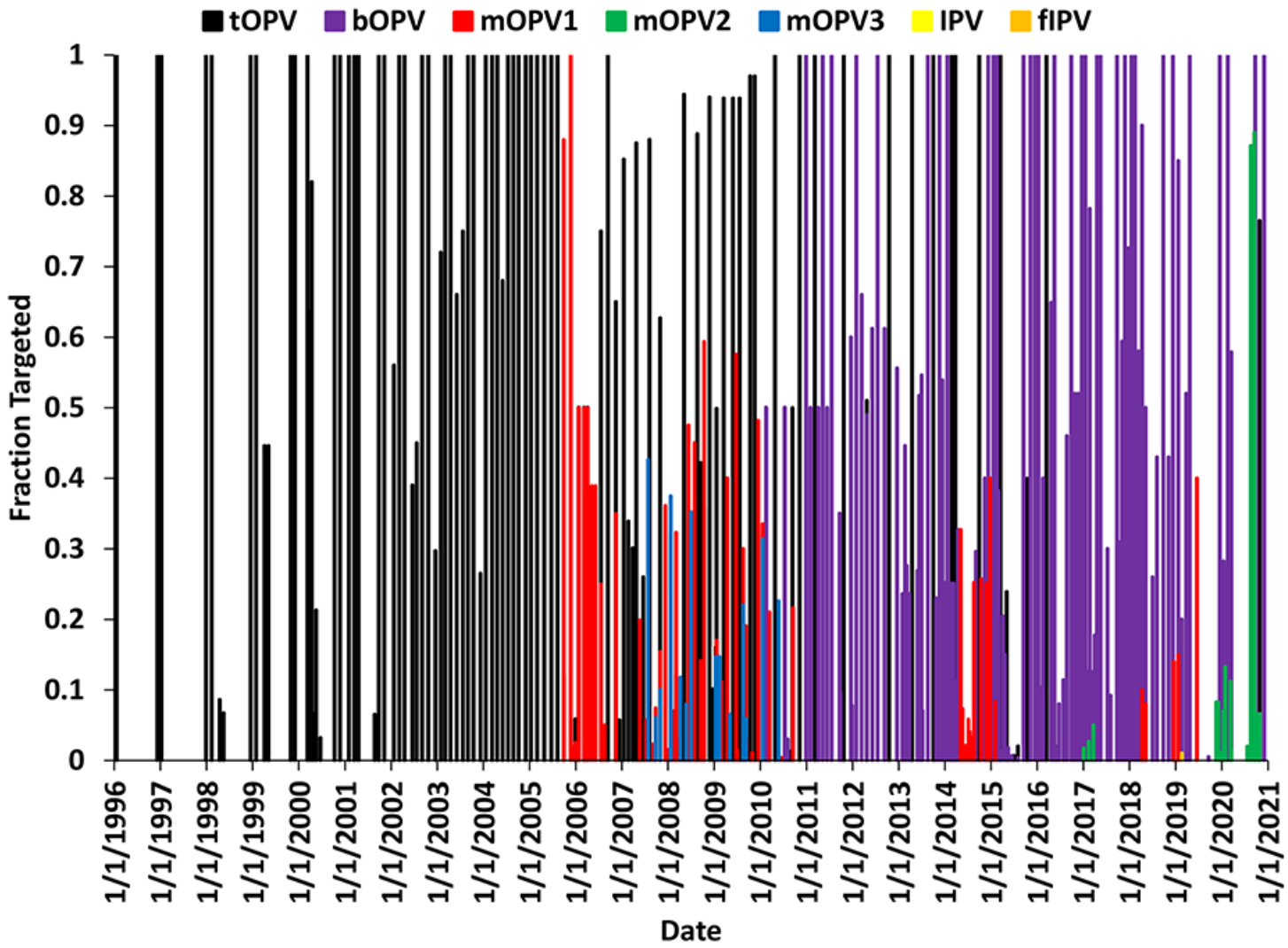

Three or more non-birth doses
Exactly two non-birth doses
Exactly one non-birth dose
Birth dose
Coverage
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1979
1984
1989
1994
1999
2004
2009
2014
2019
2024
Year

Figure 2a


tOPV
bOPV
mOPV1
mOPV2
mOPV3
IPV
fIPV
Fraction Targeted
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1/1/1996
1/1/1997
1/1/1998
1/1/1999
1/1/2000
1/1/2001
1/1/2002
1/1/2003
1/1/2004
1/1/2005
1/1/2006
1/1/2007
1/1/2008
1/1/2009
1/1/2010
1/1/2011
1/1/2012
1/1/2013
1/1/2014
1/1/2015
1/1/2016
1/1/2017
1/1/2018
1/1/2019
1/1/2020
1/1/2021
Date

Figuure 2b

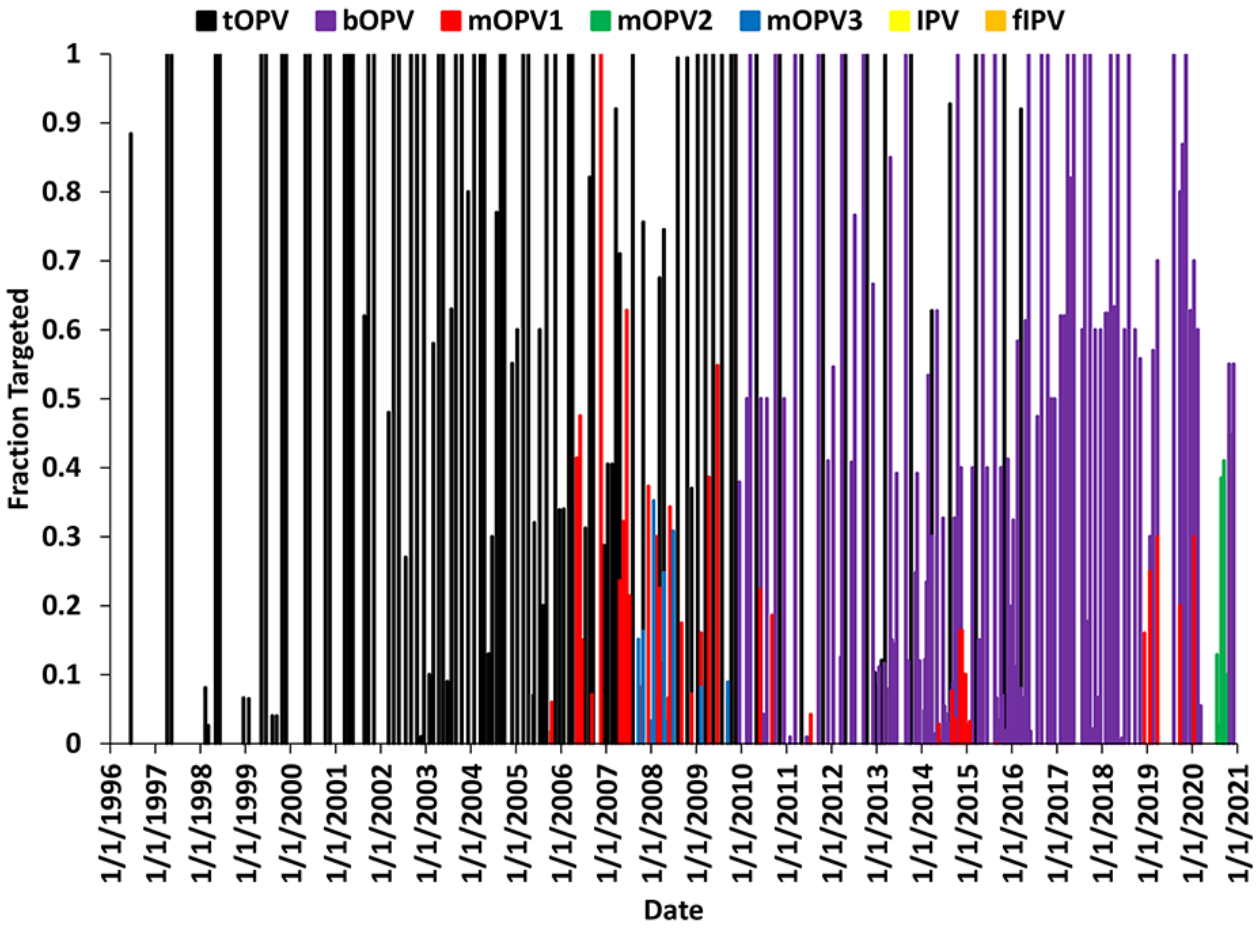

tOPV
bOPV
mOPV1
mOPV2
mOPV3
IPV
fIPV
Fraction Targeted
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1/1/1996
1/1/1997
1/1/1998
1/1/1999
1/1/2000
1/1/2001
1/1/2002
1/1/2003
1/1/2004
1/1/2005
1/1/2006
1/1/2007
1/1/2008
1/1/2009
1/1/2010
1/1/2011
1/1/2012
1/1/2013
1/1/2014
1/1/2015
1/1/2016
1/1/2017
1/1/2018
1/1/2019
1/1/2020
1/1/2021
Date

Figure 3a

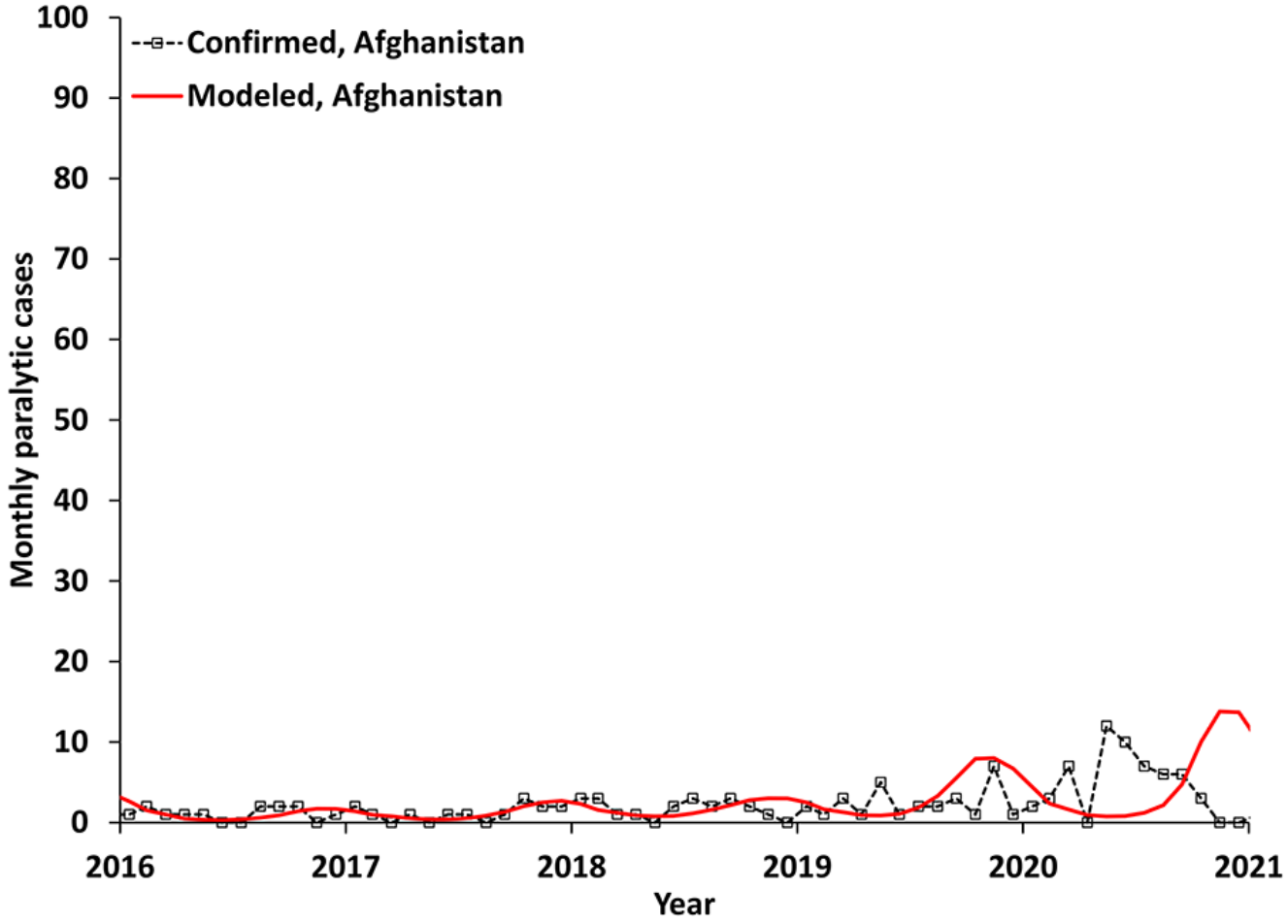
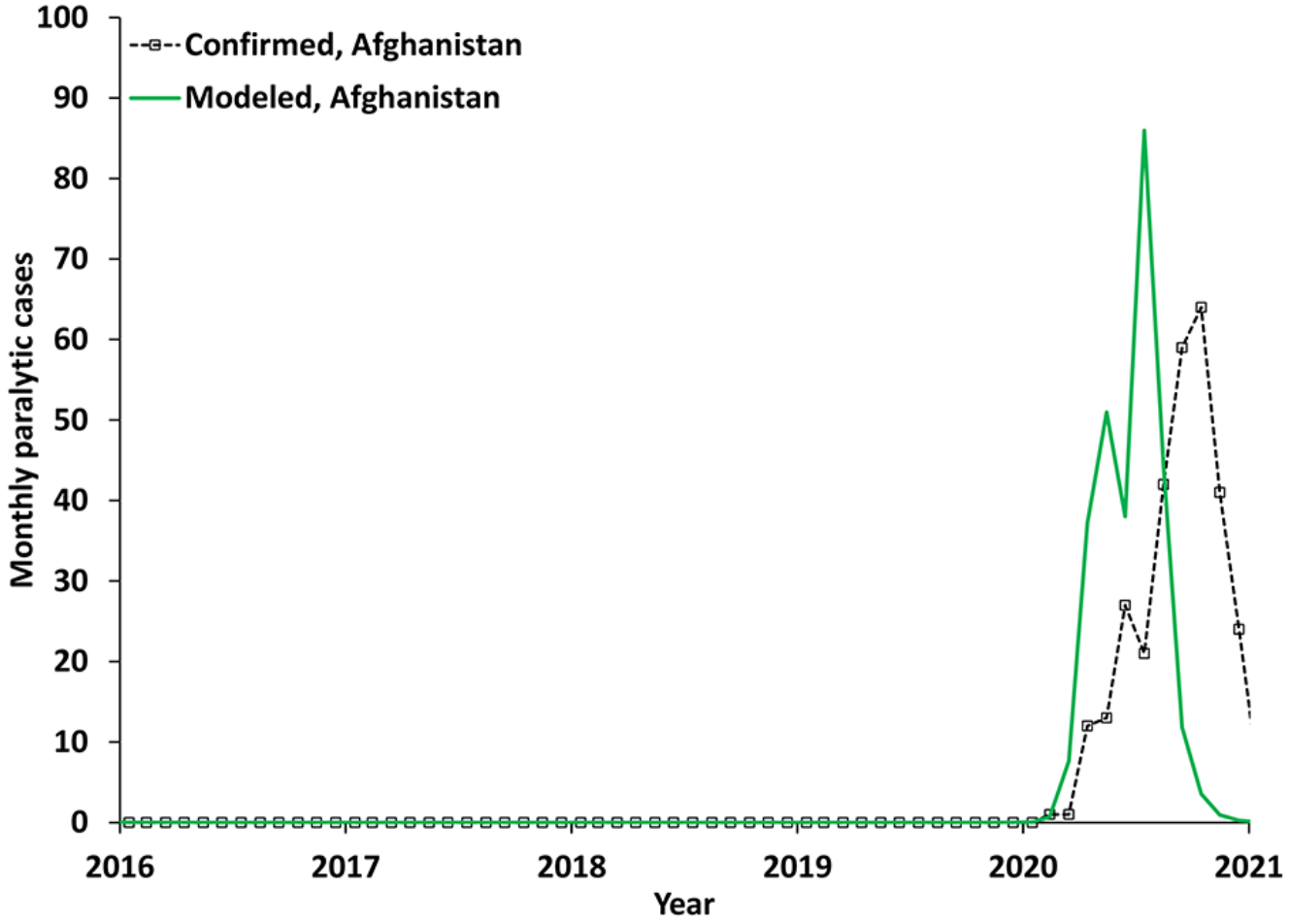

Confirmed, Afghanistan
Modeled, Afghanistan
Monthly paralytic cases
100
90
80
70
60
50
40
30
20
10
0
2016
2017
2018
2019
2020
2021
Year

Figure 3b


Confirmed, Afghanistan
Modeled, Afghanistan
Monthly paralytic cases
100
90
80
70
60
50
40
30
20
10
0
2016
2017
2018
2019
2020
2021
Year

Figuure 3a

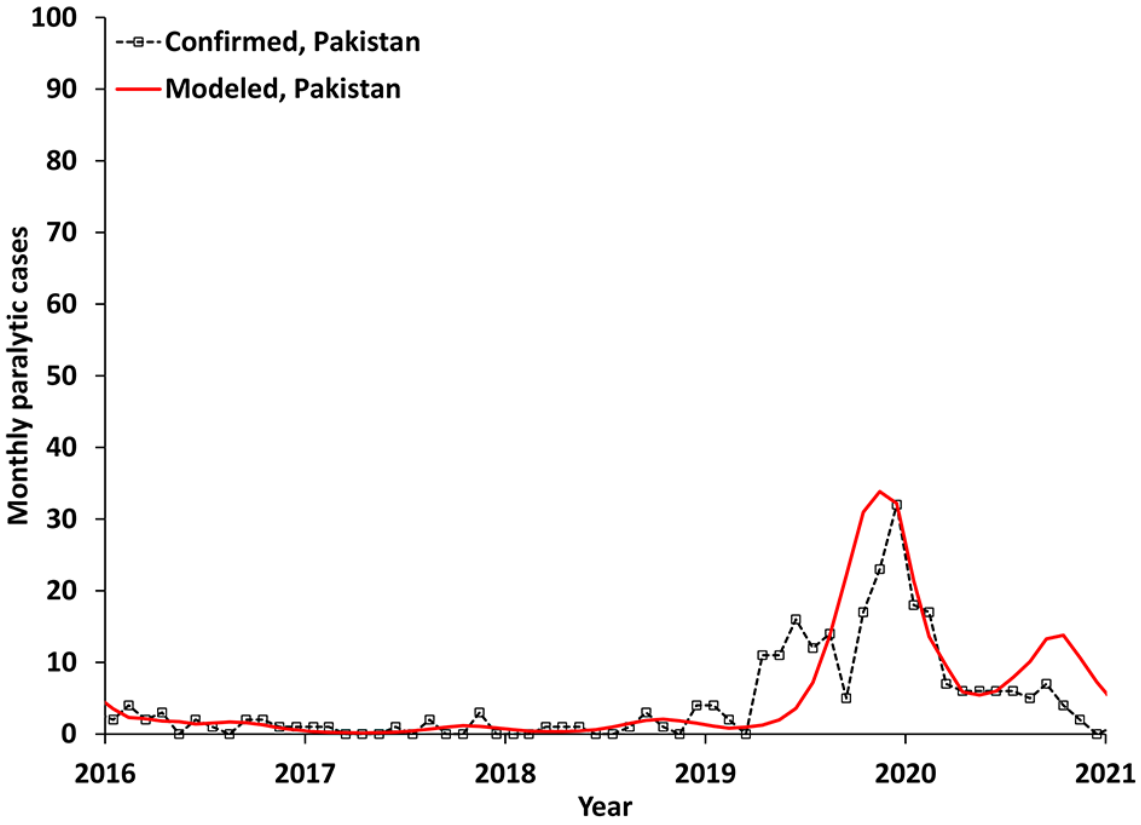


Figure 3b

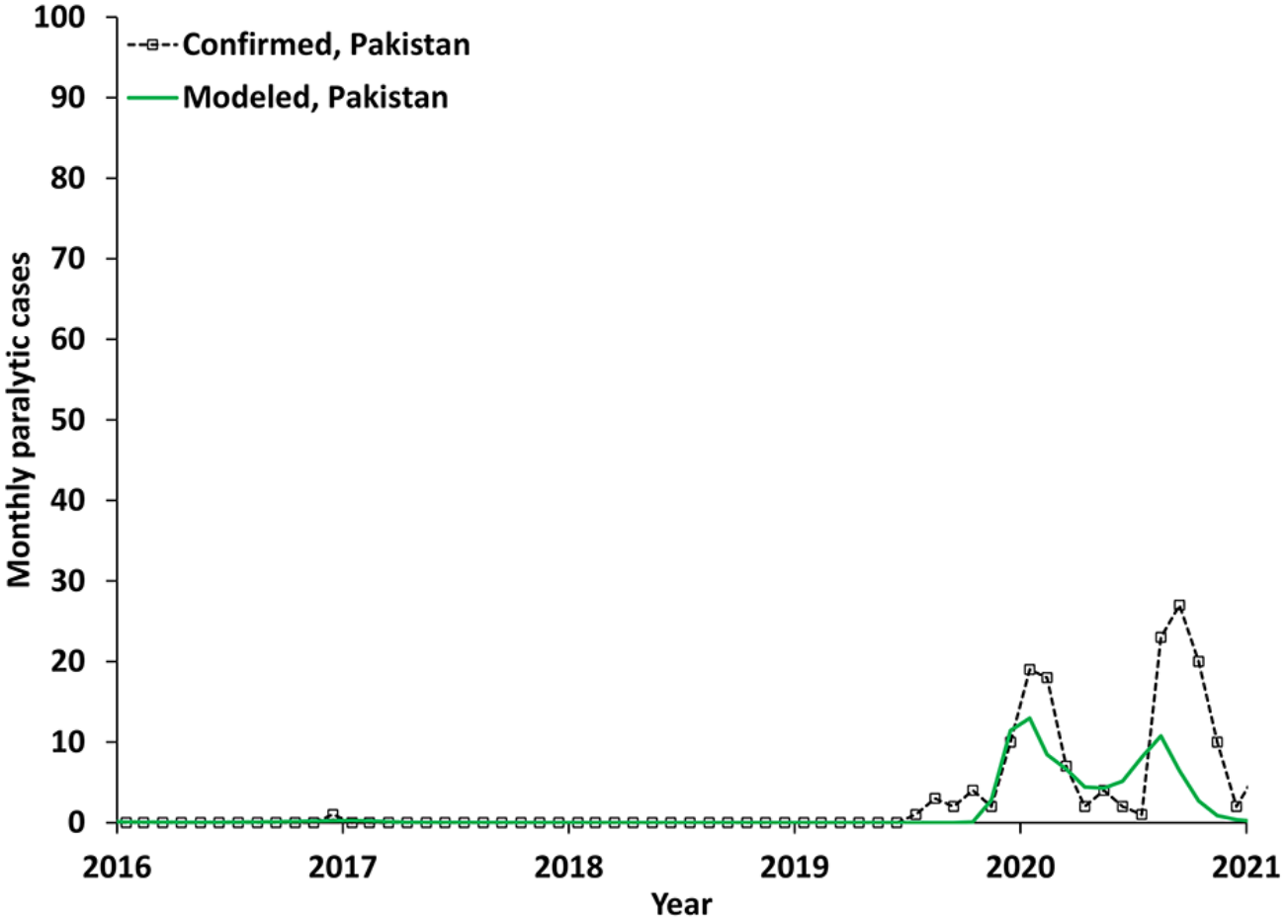

Confirmed, Pakistan
Modeled, Pakistan
Monthly paralytic cases
100
90
80
70
60
50
40
30
20
10
0
2016
2017
2018
2019
2020
2021
Year

Figure 4a

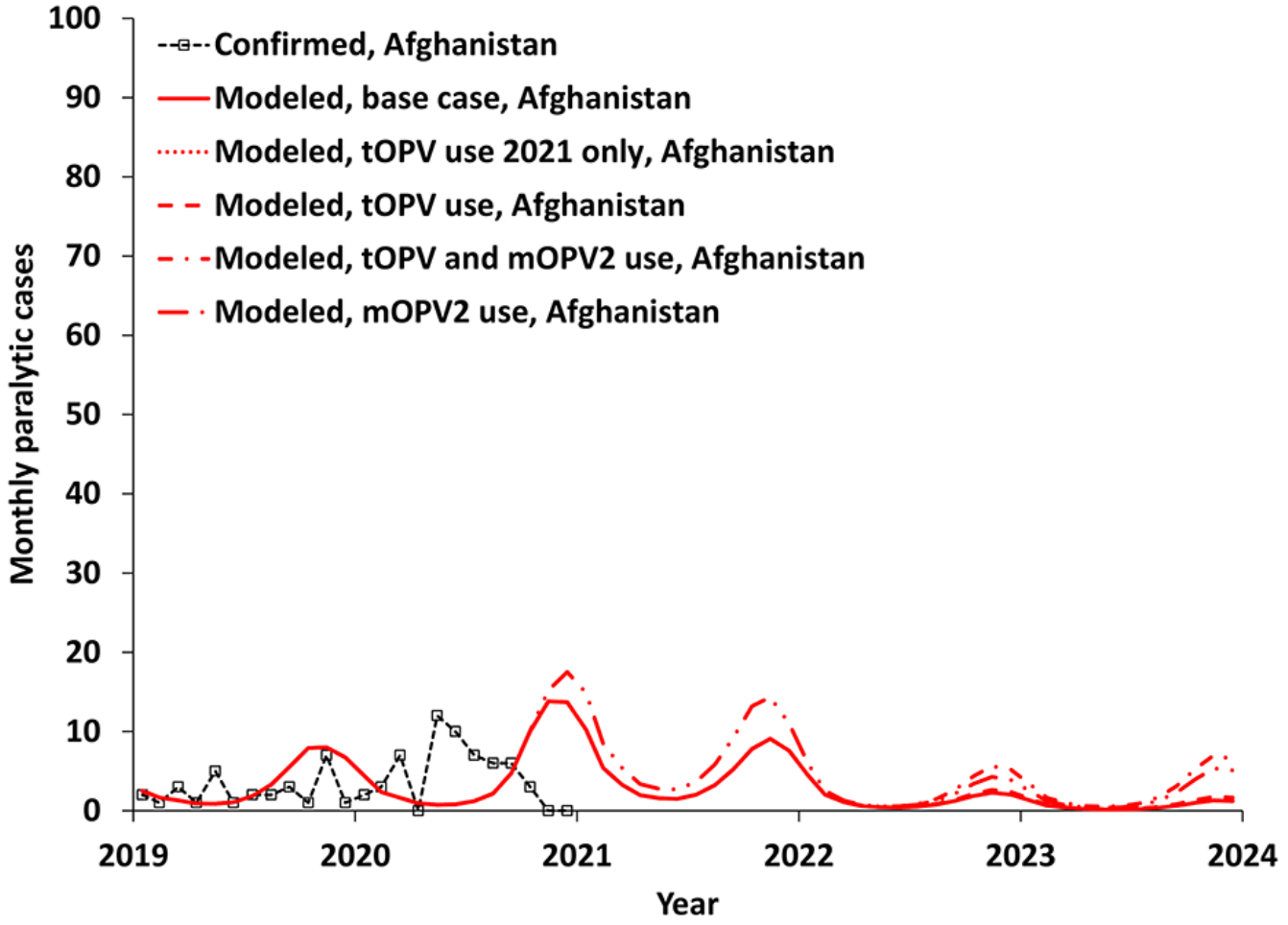

Confirmed, Afghanistan
Modeled, base case, Afghanistan
Modeled, tOPV use 2021 only, Afghanistan
Modeled, tOPV use, Afghanistan
Modeled, tOPV and mOPV2 use, Afghanistan
Modeled, mOPV2 use, Afghanistan
Monthly paralytic cases
100
90
80
70
60
50
40
30
20
10
0
2019
2020
2021
2022
2023
2024
Year

Figure 4b

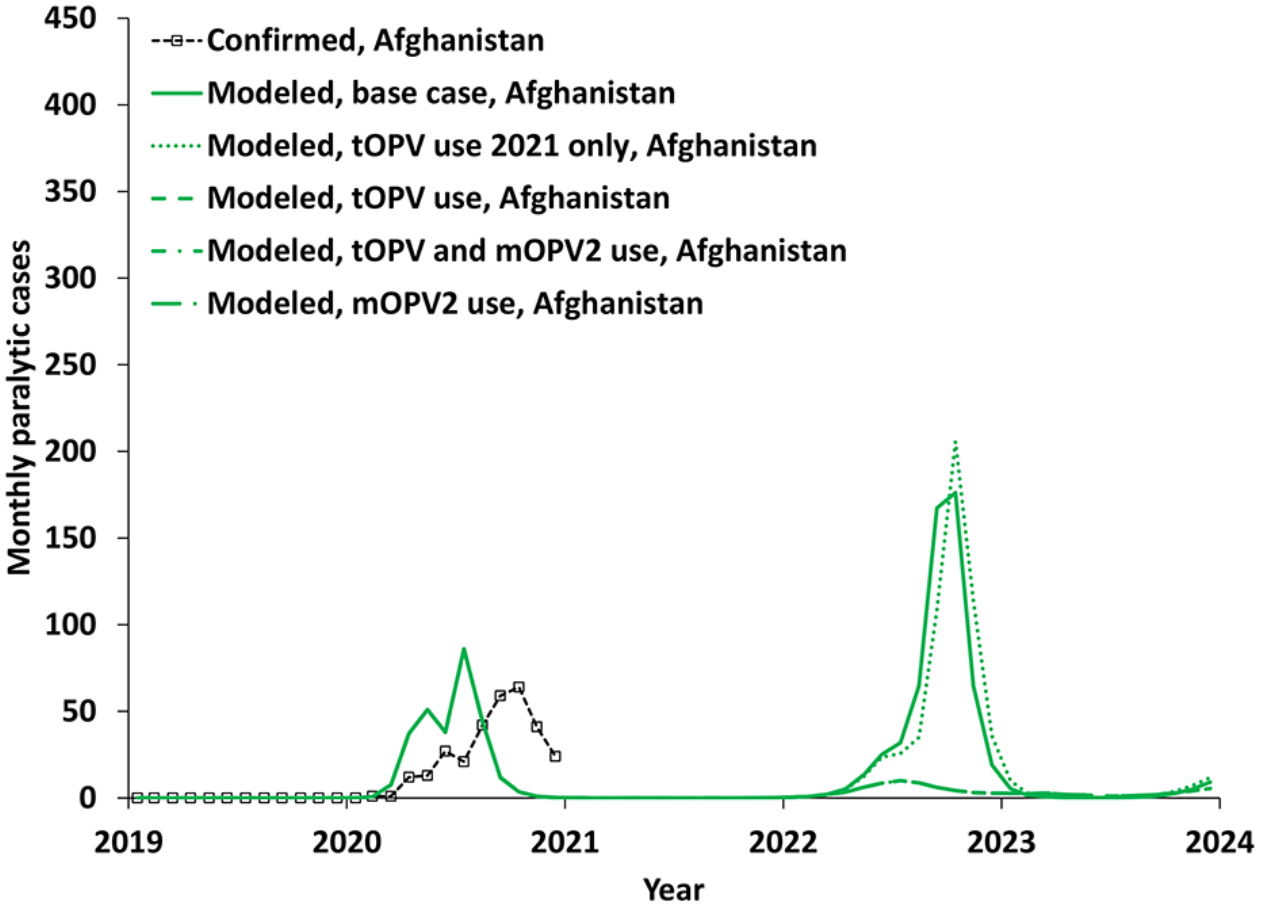

Confirmed, Afghanistan
Modeled, base case, Afghanistan
Modeled, tOPV use 2021 only, Afghanistan
Modeled, tOPV use, Afghanistan
Modeled, tOPV and mOPV2 use, Afghanistan
Modeled, mOPV2 use, Afghanistan
Monthly paralytic cases
450
400
350
300
250
200
150
100
50
0
2019
2020
2021
2022
2023
2024
Year

Figure 4a

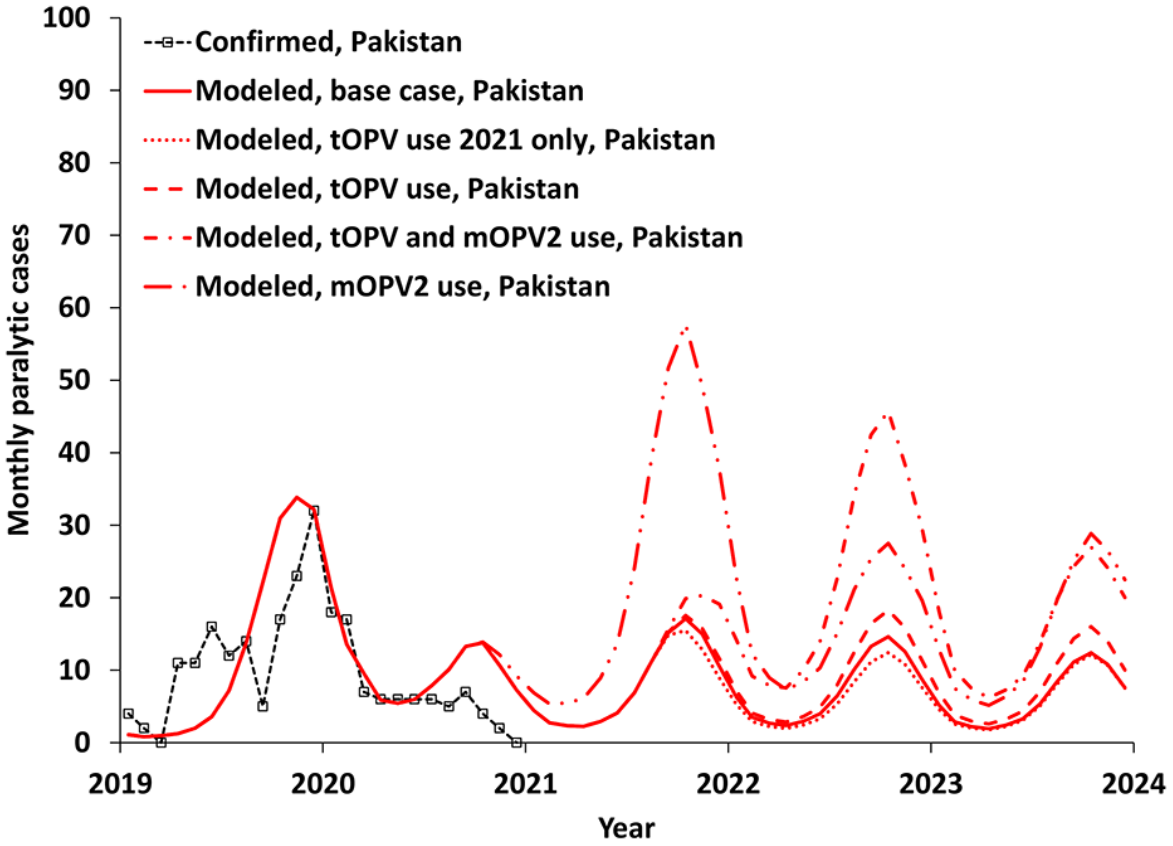
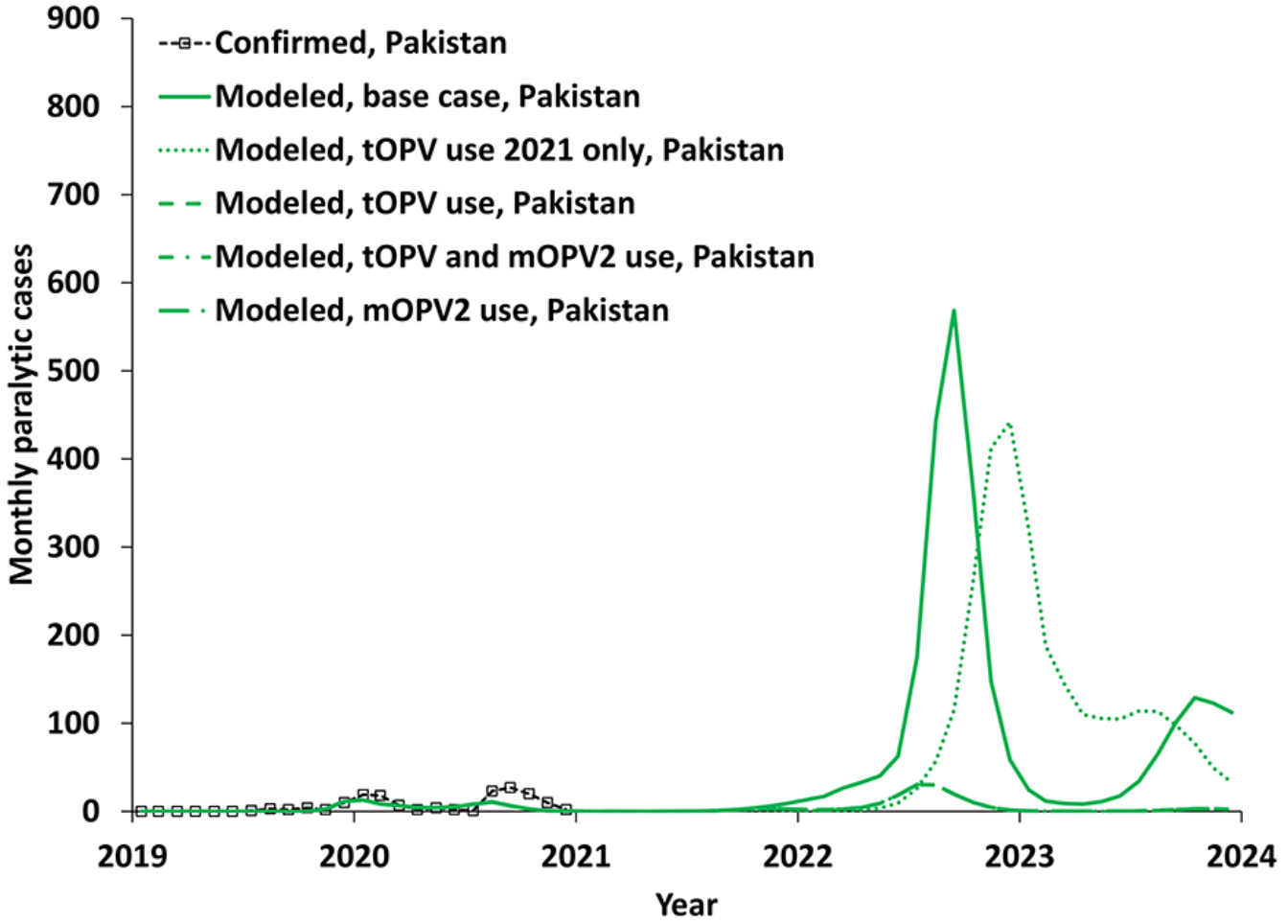

Confirmed, Pakistan
Modeled, base case, Pakistan
Modeled, tOPV use 2021 only, Pakistan
Modeled, tOPV use, Pakistan
Modeled, tOPV and mOPV2 use, Pakistan
Modeled, mOPV2 use, Pakistan
Monthly paralytic cases
100
90
80
70
60
50
40
30
20
10
0
2019
2020
2021
2022
2023
2024
Year

Figure 4b


Confirmed, Pakistan
Modeled, base case, Pakistan
Modeled, tOPV use 2021 only, Pakistan
Modeled, tOPV use, Pakistan
Modeled, tOPV and mOPV2 use, Pakistan
Modeled, mOPV2 use, Pakistan
Monthly paralytic cases
900
800
700
600
500
400
300
200
100
0
2019
2020
2021
2022
2023
2024
Year