The health impacts of COVID-19-related immunisation coverage disruption and implications for future vaccination strategies

VIMC

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Abstract

Background: There have been notable declines in immunisation coverage across the globe due to the COVID-19 pandemic. Recovery has begun but this is highly variable between countries and many regions are still experiencing cancelled and delayed vaccination activities. This disruption will lead to missed cohorts and will disrupt progress in reducing vaccine-preventable disease burden.

Methods: 23 mathematical models were used to estimate the burden due to twelve vaccine-preventable diseases under various vaccine coverage scenarios. The impact of vaccination was then calculated given pandemic disruption.

Findings: We find widespread disruption to vaccination activities but project recovery in vaccine impact in future years assuming sustained effort. Most WHO regions included saw some stagnation or backtracking in burden averted through vaccination with the most notable increases in burden were seen for the European region. Vaccine impact varied by region with WHO AFRO generally seeing the lowest number-needed-to-vaccinate to avert death, though this varied temporally. We estimate approximately half of countries had higher-than-expected burdens for the post-COVID-19 cohorts suggesting that some cohorts had been missed for vaccination.

Interpretation: Our analysis is the first broad-scale vaccine impact modelling exercise informed by data on coverage achieved in 2020. Our projections highlight some loss in progress but we emphasise the progress already made, and that is possible through continued focus and service provision, to benefit missed cohorts.

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Research in context

Evidence before this study We searched PubMed on 18th May 2022 for studies published after 1st December 2019 in English with search terms ((COVID-19 OR SARS-CoV-2) AND (disruption OR interruption OR cancel*)) AND (vacc* OR immun* OR coverage). Studies were included if they focused on disruption to vaccination activities due to the COVID-19 pandemic. We found 1181 studies where 69 met the inclusion criteria. These studies showed evidence of notable declines in immunisation activities across the globe related to the COVID-19 pandemic. These have included reductions in achieved routine coverage, cancellation or postponement of campaigns and missed cohorts. Immunisation was most disrupted in the early months of the pandemic, particularly March to May 2020; however, the amount of recovery seen varied by country, age-group and vaccine. It has also been noted that some schedules were more affected than others with vaccines given at birth seeing smaller reductions than those given later. Despite the far-reaching ramifications of these immunisation disruptions, there are still key uncertainties in the pathway to recovery and catching up and there have been relatively few examinations of how these disruptions affect vaccine impact and prioritisation.

Added value of this study Our study is the first large scale evaluation of vaccine impact and missed vaccination in terms of morbidity and mortality averted since the first COVID-19 disruption data has become available through projected estimates and WUENIC. We highlight the magnitude to the change in impact, tracked through cohorts missed and coverage disruption and project the duration in disruption given best-estimates of future coverage. We also identify regions and cohorts who may especially benefit from additional vaccination activities either because their projected burden is higher than expected or because they have a low number-needed-to-vaccinate to avert one disease outcome.

Implications of all the available evidence The COVID-19 pandemic has had varying impacts to immunisation activities with variation by geographic region, vaccine and schedule contributing to a complex landscape for prioritisation. Our study emphasises the importance of timely vaccination and identifies cohorts and regions that may be particularly benefited by catch up activities. We also reiterate the enormous benefits of sustained effort in vaccination.

1 Introduction

Prior to 2020, immunisation efforts, including progress on the Global Vaccine Action Plan 2011-2020 (GVAP), saw widespread stagnation. DTP3 coverage has hovered around 85% since 2010, and only 64% of countries have achieved the coverage target of 90%. Over 19 million infants still lacked a full course of vaccines, highlighting the persistent inequities in immunisation access [1]. Further declines in national ownership and political prioritisation placed other countries at risk of backsliding from currently met targets.

There have been notable declines in immunisation coverage across the globe due to the COVID-19 pandemic and interventions, with disruption varying geographically, but also by vaccine and vaccine delivery method. Countries, especially LMICs, have also faced further delays in supplementary immunisation activities, including campaigns, increasing the risk of outbreaks and disease burden. Similarly, inequity was exacerbated by, and exacerbated the disruption due to COVID-19, [2, 3, 4] and this has increased the number of zero-dose children [5]. Past research suggests groups more likely to be affected by zero-dose status and vaccine inequities include children in lower wealth quintiles, children whose parents have not received formal education, ethnic or religious minorities, and women [6]. These effects are anticipated to have detrimental effects for public health, with estimates expecting 5% fewer vaccinated persons and 5.22% more vaccine-preventable deaths for vaccination activities occurring between 2020 to 2030, even when IA2030 goals are met [7].

Vaccination, however, remains one of the most cost-effective strategies to reducing global morbidity and mortality, saving an estimated 2-3 million lives per year [8]. Over the past two decades, several global policies and initiatives have increased full vaccination rates of children in low- and middle- income countries (LMICs) from 50% to 80%, decreasing not only vaccine-preventable disease burden, but also improving social and health equity, promoting positive childhood development, and decreasing economic burden from medical expenses and financial risk. Immunisation also has one of the greatest return on investments, with an estimated economic return of 19.8 $US from 2021 to 2030 for each dollar invested using a cost-of-illness approach against ten pathogens pre-pandemic [9].

Data and information on disruption is only now becoming available, and despite disruptions, early estimates show more children were vaccinated in December 2020 compared to the same period in 2019, due to a global effort to increase immunisation uptake [6, 7]. However, the COVID-19 pandemic has had varying impacts on immunisation activities, contributing to a complex landscape for prioritisation. There has been a continued emphasis on timely catch-up campaigns to reduce outbreaks, target missed cohorts, and bring vaccine-preventable diseases (VPDs) back on track towards existing elimination targets; though some projections suggest that despite current efforts, even minor delays and disruptions can have lasting impacts on disease burdens and elimination goals [10, 11, 12, 13, 14]. Addressing these existing immunity and coverage gaps will require a change in existing vaccination strategies.

This study is the first large-scale evaluation of vaccine impact and missed vaccination in terms of morbidity and mortality averted since the first COVID-19 disruption data has become available through projected estimates and WUENIC. Our study emphasises the importance of timely vaccination and identifies cohorts and regions that may be particularly benefited by catch up activities. We also reiterate the enormous benefits of sustained effort in vaccination.

2 Results

2.1 Vaccine coverage disruptions in 2020 and beyond

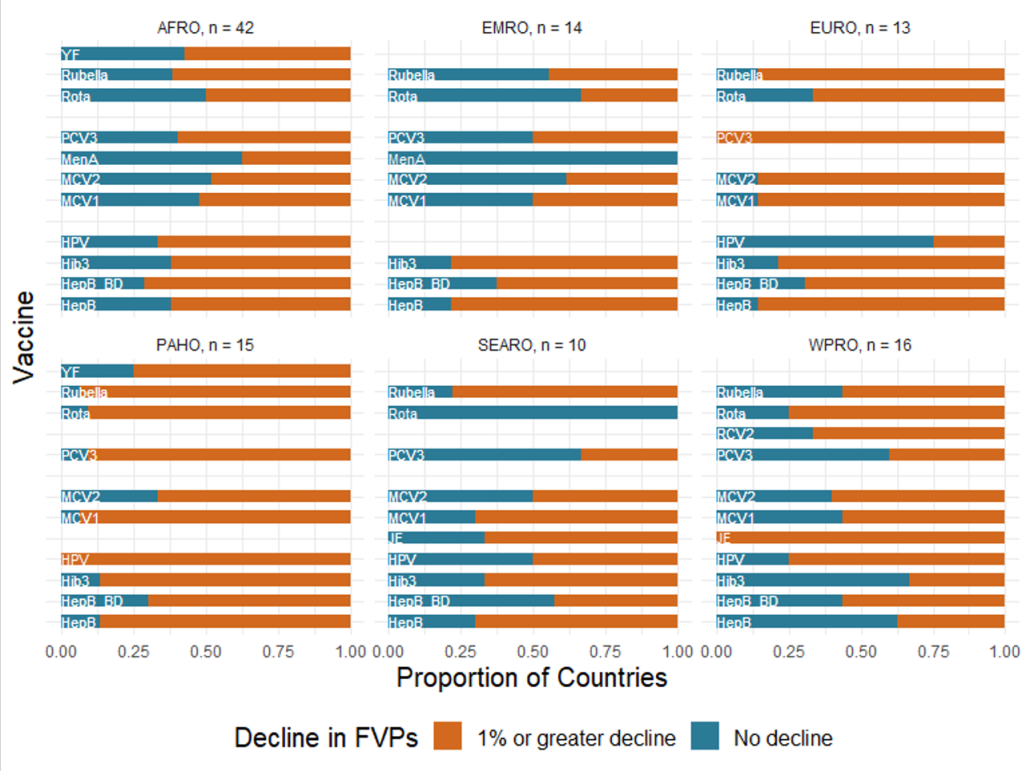


Figure 1: Proportion of countries showing a 1% or greater decline in fully vaccinated persons during routine immunisation activities between 2019 and 2020; n indicates the number of countries represented in each WHO region though for YF, MenA and JE n may be lower.

Figure 1 shows the proportion of countries by vaccine in each region that has experienced a drop in FVPs based on the latest WUENIC data, and information from complementary sources, see section A for full details. These estimates suggest that PAHO and EURO were among the WHO Regions with the greatest disruption; for each vaccine in the Americas, at least 50% of countries were impacted. Similarly, for all vaccines in EURO, except HPV, over 50% of countries faced a decline. Notably, AFRO and EMRO faced lower impacts, but for some vaccines, disruption was still widespread such as for HepB birth dose. The most extreme examples are for PCV3 in EURO, where all included countries experienced disruption. Conversely, no countries in EMRO experienced a drop in FVPs for MenA and no countries in SEARO experienced drops in rota coverage although the number of countries included for these region-vaccines is small. With the exception of MenA and Rota, the proportion of countries affected with COVID-19 disruption across all vaccines in all Regions was at least 25%.

When we compare numbers of FVPs directly between the reference year, 2019, and subsequent years we can begin to see the projected recovery in some Regions, but not all, see figure 2. WPRO was projected

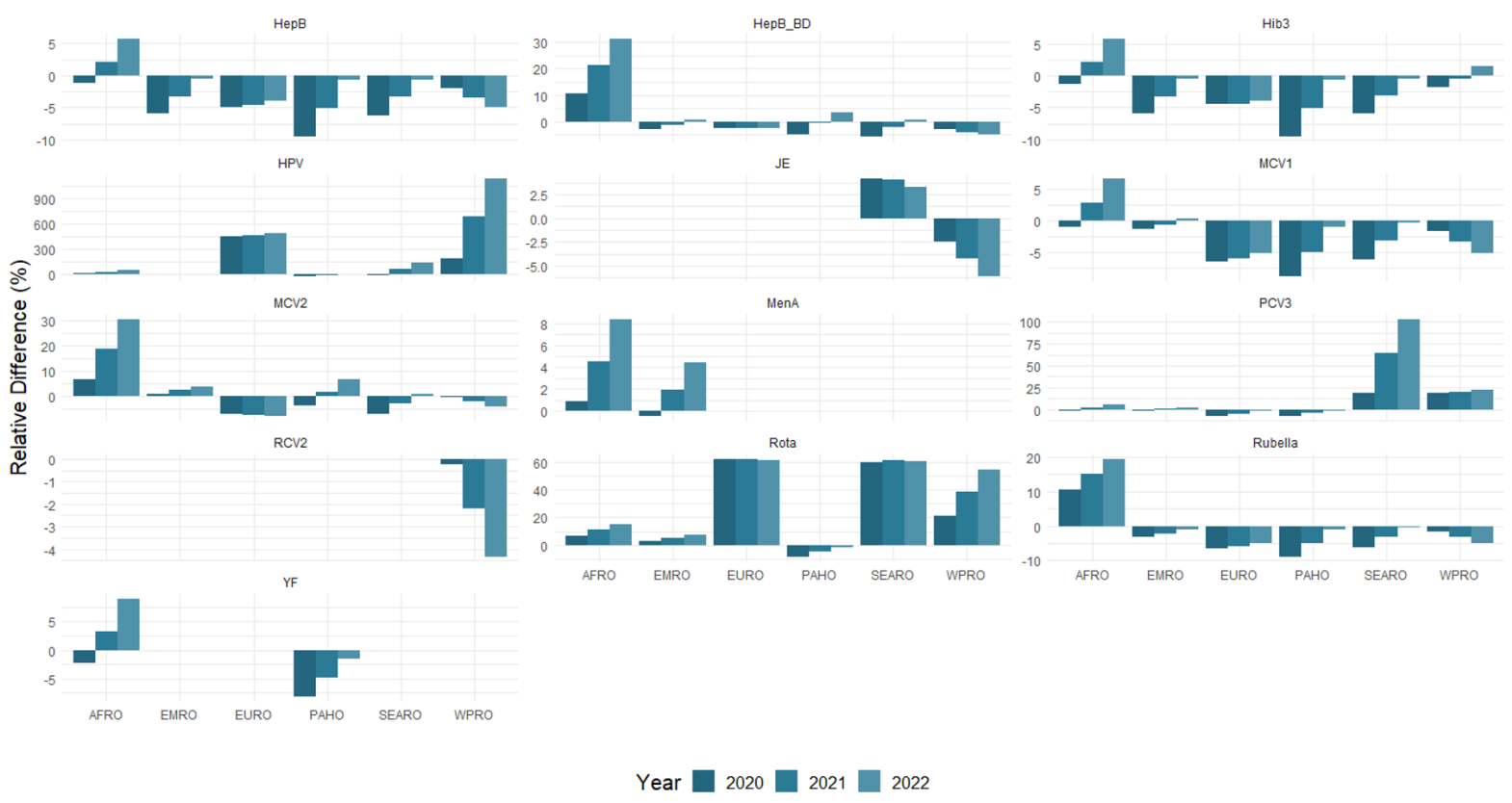


Figure 2: Projected relative difference in FVPs from routine immunisation services between 2019 and 2020, 2021, and 2022, grouped by vaccine and WHO region.

to have the greatest number of coverage disruptions continuing into 2022; all vaccines but Hib3, HPV, PCV3 and Rota showed worsening trends for FVP coverage. Only MCV2 in EURO showed a similar trend. The single greatest projected decline in FVPs, was for HPV in the SEARO Region in 2020, with a relative difference of -28.2% compared to 2019 estimates. By 2022, however, there was a near recovery to 2019 coverage levels, with a projected decline of -1.9%. As a result of vaccine introductions, Rota and HPV show the greatest improvement in FVPs, especially in EURO, SEARO, and WPRO Regions, with the greatest overall improvement in WPRO for HPV in 2022, where the relative difference in FVPs compared to 2019 is 1,127%.

2.2 Projected burden

The variations in the burden projections illustrated in figure 3 are dependent on the coverage over time; some of the diseases in which we would have anticipated declines in burden have seen resurgences as a result of COVID-19 disruption in 2020. The estimated burden for these diseases, however, show a recovery period for the subsequent years. All regions saw either stagnation or some backtracking following the reference year, 2019. However, the most apparent increases in burden were projected for EUR. Figures D.6, D.7 and D.8 show the diverse trends by vaccine and country with the most notable increases in burden seen for HepB.

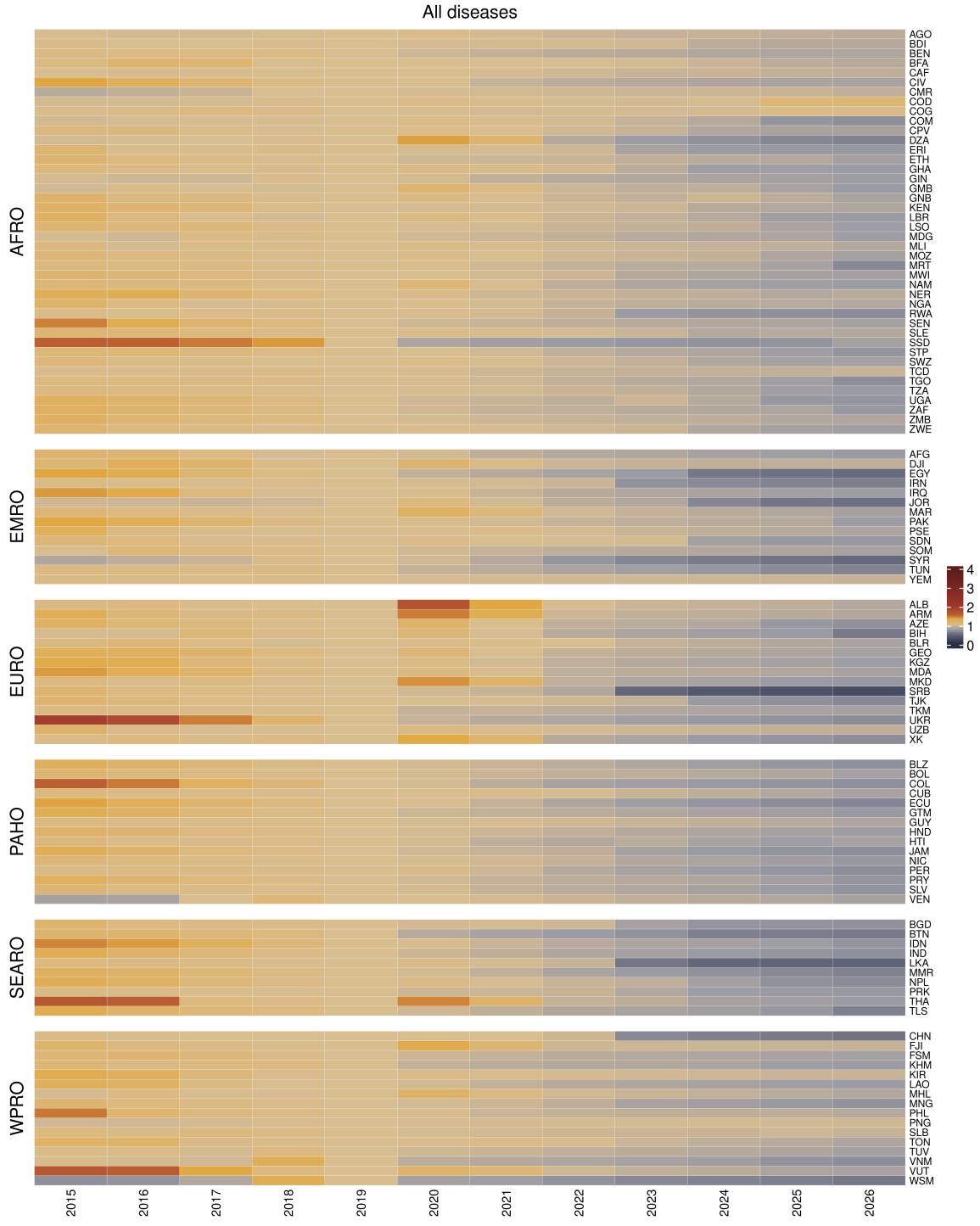


Figure 3: Deaths per 100,000 live births with colour scale normalised by the estimated burden for 2019.

2.3 Number Needed to Vaccinate to avert one disease outcome

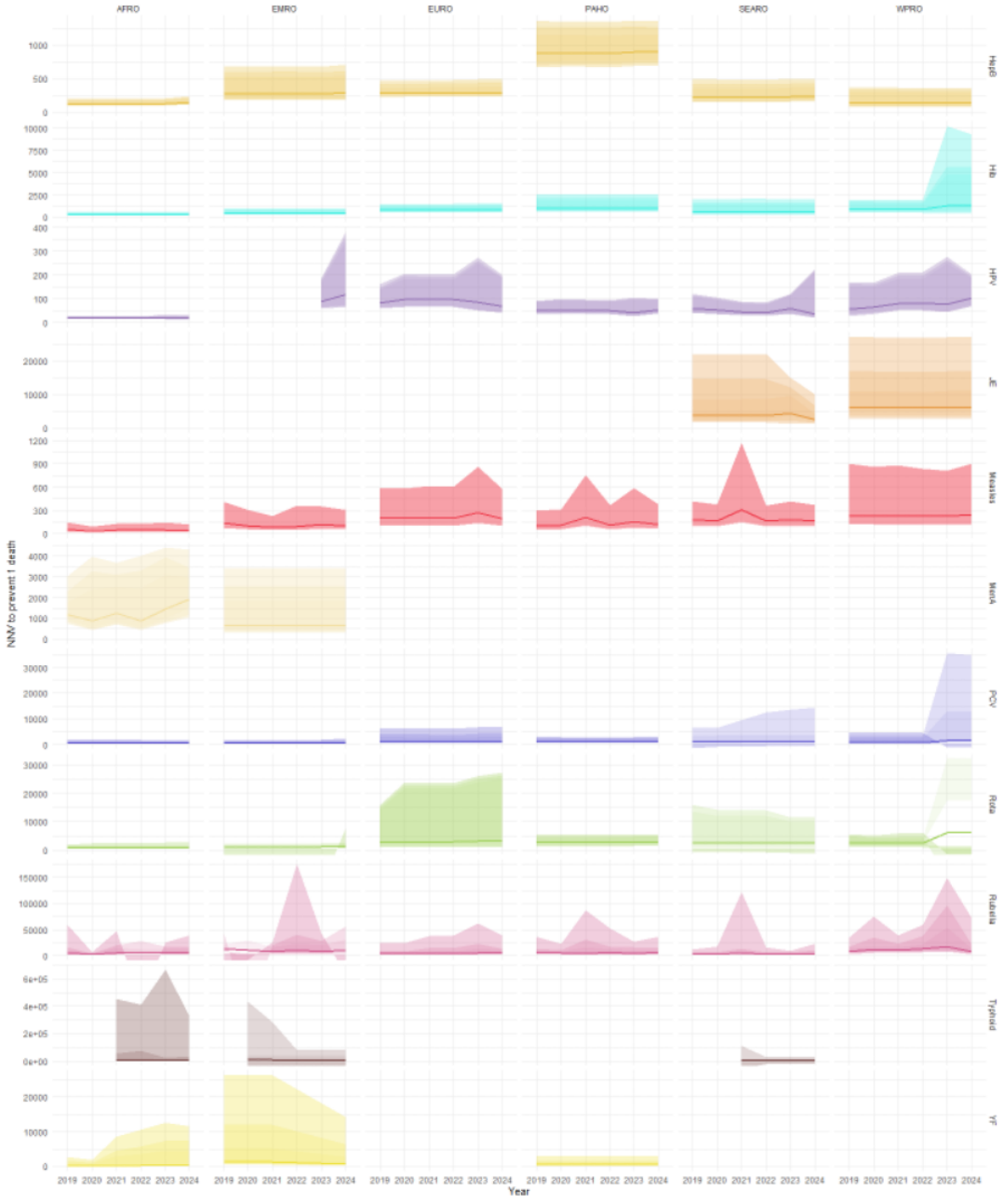


Figure 4: Number needed to vaccinate to prevent one death, stratified by WHO region and disease from 2019-2024. Transparent ribbons show 50%, 80%, and 95% confidence intervals for the point estimates.

Figure 4, and figure D.9 in the supplementary material, show a variable picture by region, where WHO AFRO generally has the lowest NNV, and WPRO, EURO, or PAHO have the highest; this is true regardless of the burden outcome averted.

There is further variation by vaccines, where HPV has the lowest NNV, and Rota, Rubella, and JE have the highest. NNV highlights where the most benefit can be derived from vaccination and illustrates the variation over time, geography and vaccine. From 2022 onwards, trends in WPRO in Rota, PCV, and Hib show significant increases in NNV; HPV shows a decline for all Regions in 2023. Excluding WPRO in the aforementioned diseases, trends for HepB, Hib, JE, PCV, Rota, and YF remain relatively stagnant across all Regions. Measles, HPV, Rubella, and MenA have the greatest variance, with SEARO showing the greatest variance across measles, WPRO and EURO for HPV, WPRO for Rubella, and AFRO for MenA. While these trends remain the same for deaths and DALYs, it should be noted that the lowest NNV for DALYs is consistently measles in the AFRO Region.

The full table of NNV values can be found in supplementary table E.2.

2.4 Expected vs. estimated decline in burden by cohort

Figure 5 presents an estimation, across all diseases, of whether progress in reducing burden per cohort has been affected by COVID-19 related disruptions. In the majority of countries (70 out of 112), there is larger burden for the 2020-2022 cohort than expected if the 2015-2019 linear trend had continued. In AFRO, countries including Senegal and Cote d'Ivoire saw a reduction of progress whereas Cameroon and the Democratic Republic of the Congo (COD) had better than expected progress and, notably, COD moved from an increasing trend of burden per cohort, to a decreasing trend. Similar heterogeneity is seen for the other regions. For the 2023-2024 cohort the majority of countries (23 out of 42) in the AFRO region had lower-than-expected burdens compared to the the 2015-2019 trend. Approximately half of all countries (55 out of 112) had lower-than-expected burdens.

We see substantial variations between diseases, as shown by the disease-specific figures in supplementary section D.3. For the 2020-2022 cohort, HPV projected an improvement in most regions/countries; however this is mostly driven by new introductions. In contrast, Hib and PCV saw stagnations in progress, especially in the WHO AFRO region. HepB is variable between regions with an overall decrease in progress in the EURO region but a general improvement in the AFRO region. Measles, despite reasonable concerns over missed cohorts and outbreak potential, saw better than expected performance in the majority of countries across all regions except SEARO. MenA sees almost unanimous reductions in progress across all study countries, only Rwanda, the Gambia and Chad had better-than-expected performance. In rubella and YF, a mixed picture is seen but the country-specific changes are, at times, dramatic. For example, Uganda completely reverses the trend of declining the burden of YF to a severe increase of over 100%. Similarly Syria sees huge increases in rubella burden compared to pre-pandemic cohort trajectories.

For the 2023-2024 cohort, HepB in the AFRO region showed even stronger improvements than in the 2020-2022 cohort, including for several countries where the 2020-2022 cohort had actually shown a lower-than-expected improvement. The shift of several countries in the AFRO region from higher-than-expected to lower-than-expected burdens is likely driven by these estimates for HepB.

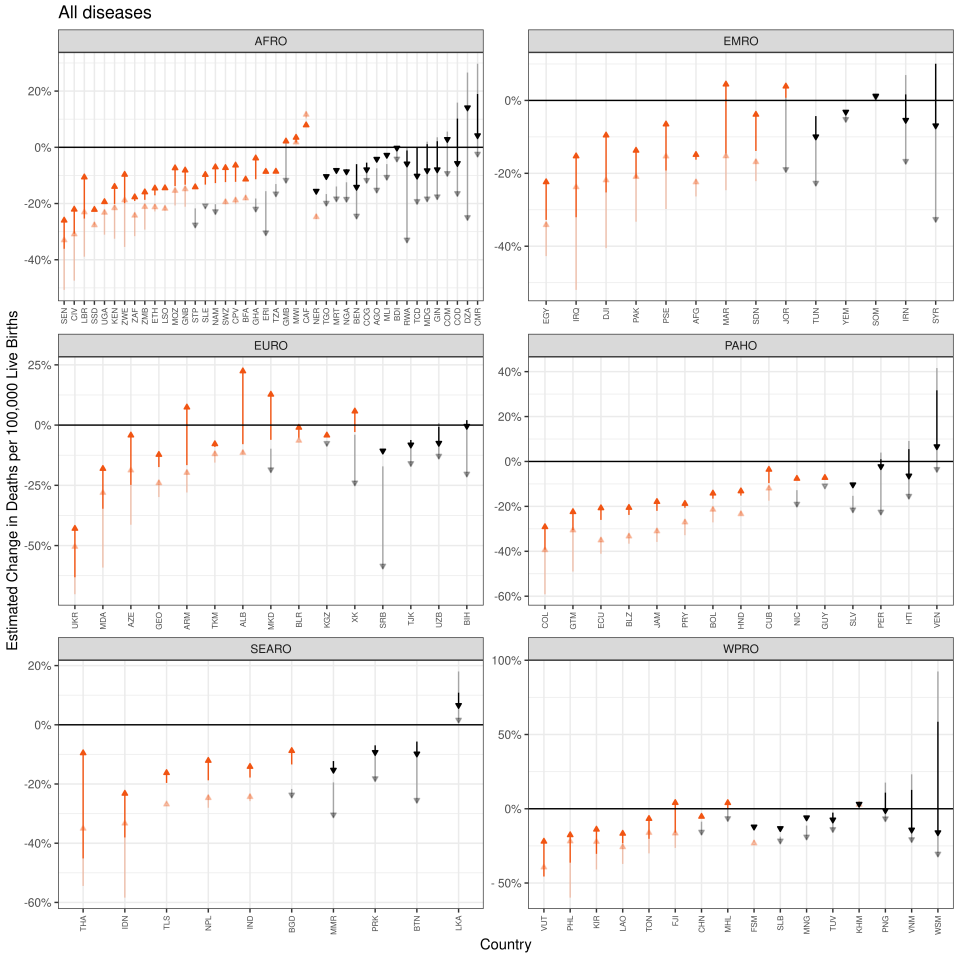


Figure 5: Expected vs. estimated percent change in deaths per live birth from the 2015-2019 (pre-COVID) cohort to the 2020-2022 post-COVID cohort (opaque arrow) and to the 2023-2024 post-COVID cohort (transparent arrow). The base of the arrow is the percent change in deaths per live birth from the pre-COVID to the post-COVID cohort calculated by linearly extrapolating the 2015-2019 yearly trend in modelled estimates; the point of the arrow is the percent change in burden from the pre-COVID cohort to the post-COVID cohort actually estimated by the models. Arrows shown in orange (i.e. arrows pointing up) indicate larger post-COVID burdens than if the 2015-2019 linear trend had continued; arrows shown in black (i.e. arrows pointing down) indicate lower post-COVID burdens than if the 2015-2019 trend had continued. The horizontal line at 0% indicates a post-COVID burden exactly equal in line with the 2015-2019 linear trend continuing. Positive values on the y-axis indicate larger burdens in the post-COVID cohort than in the 2015-2019 cohort (but not necessarily larger burdens than expected, if the 2015-2019 trend showed increasing burdens).

2.5 Achieving Global YF epidemic and MenA Elimination Targets in the Face of COVID-19 Immunisation Disruption

Figure 6: Total FVPs for YF from 2017 to 2026, showing both campaign and routine immunisation activity as one value. Target y-intercept value is calculated as 50% of the target population in 2022.

Examining YF and MenA elimination targets through 2024 show significant variation as a result of COVID-19 disruption. Though global estimates show that MenA targets will be achieved, individual country-level results show minor increases alongside declines; notably it is Tanzania and Rwanda's decline in deaths averted that has the greatest impact on the global target. Similarly, although most countries will achieve their YF targets by 2022, there are notable exceptions, including Kenya, Nigeria, the DRC, and Uganda, who still fall below the FVPs target by 2026, and Angola, the Central African Republic, and Guinea who will reach it by 2024. Angola, Liberia, and Gambia also show evidence of COVID-19 disruption in immunisation in 2020 and/or 2021, with all of these achieving recovery over a subsequent two-year period.

Figure 7: Mean meningitis A deaths through 2024 in the AFRO Region, with the pink line representing the target of a 70% reduction in 2015 deaths, to be achieved by 2030.

3 Discussion

We projected the impact of vaccination for twelve vaccines across 112 countries considering the latest available vaccination coverage information including disruption in activities due to the COVID-19 pandemic. We find at least 25% of countries across all Regions and vaccines were affected by some disruption and in some cases this disruption was projected to continue through 2022. Due to this disruption, burden per live birth showed some increase post 2020 with the most notable changes seen countries in the European Region. More generally, there was heterogeneity over time and by Region in the number-needed-to-vaccinate (NNV) to avert one disease outcome with AFRO consistently having the lowest NNV. Regarding future targets and projected performance, in many cases, cohorts born in 2020-2022 compared to 2023-2024 fared less well in terms of burden per live birth than projected given the pre-pandemic trends. This includes both reversal and maintained coverage in progress for some country-vaccine combinations. As a result, whilst the overall message of reaching targets for control of YF and MenA is positive, there are notable exceptions.

Our results show a diversified picture of the current state of immunisation coverage and vaccine impact given the latest pandemic disruptions. There is notable disparity between vaccines and Regions in terms of the implications of disruption. Whilst disruption appears most apparent in countries in the European Region, the relative benefits of increased vaccination may be higher elsewhere either due to a lower NNV meaning fewer doses are needed to avert mortality, or through addressing missed cohorts. It is possible that disruption to vaccination activities, and its ramifications, may continue beyond 2022. The road to recovery also varies by the country-vaccine considered affected not only by the targets at the end of the decade of vaccines but also by vaccine introductions and progress to date. Yet, our results highlight that reaching elimination targets are still feasible given sustained and targeted commitment.

We utilised available data on vaccination activities as of mid-2021. However, we model coverage changes annually and have projected from 2021 onwards. As such, we do not capture the variation month-by-month which was seen especially during the pandemic disruption and we may have been too optimistic, or pessimistic, about pandemic recovery. In multiple studies it is noted that immunisation was most disrupted in the early stages of the pandemic particularly March - May 2020, or the first lockdown-equivalent non-pharmaceutical intervention [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33]. Some exceptions include Nigeria, Uganda and Portugal where either vaccination dropped at different times or not at all [34, 35, 17]. The return to pre-pandemic levels of coverage has also been heterogeneous. Recovery has begun in a number of countries[1] and in some cases this has resulted in almost pre-pandemic levels of coverage[2]. However, in most cases, disruption continued and may have resurged since the publication of earlier data. For example, the second WHO pulse noted only 11 out of 61 surveyed countries had improved coverage [32], Additionally, by the end of 2021, whilst campaigns had resumed, Ho et al. noted 16% of campaigns were still postponed or cancelled, the majority of which were in Africa [29]. Unfortunately it will take years, and further data collection, to understand the full toll of pandemic disruption on vaccination activities.

We have included information on vaccination activity disruption; however, the inclusion of disruption in transmission due to non-pharmaceutical interventions (NPIs) is only present in some models and information on transmission disruption is still extremely sparse. We do not expect disruption due to COVID-related NPIs to affect all the diseases mentioned here equally, for example JE and YF are unlikely to be affected to the same extent as measles. Similarly, the impact of NPIs on current and future transmission is still unclear; a recent study on RSV and influenza suggested short-term reductions in transmission may be followed by larger outbreaks in future [40]. Similarly, studies in Germany and China examined the impact of NPIs on all notifiable diseases and found substantial reductions in the early months of the pandemic followed by resurgence and outbreaks when NPIs are relaxed [41, 42]. Studies like these are only feasible where data is routinely collected and available and as such, they are few in number. It is unclear whether the countries included in our analysis will have similar affects especially as there been substantial variation in the type, stringency and timing of NPIs used [43]. Notably, China did not see a decrease in measles incidence, likely due to high vaccination coverage, a result which may heavily contrast with other countries considered. In order to address this limitation, there have been some initial modelling studies that have included theoretical transmission disruption scenarios; Fu et al. examined the implications of COVID-related disruption to measles vaccination and the vaccine impact was predicted to drop by 0.3% over 2000-2050 [44]. Similarly, Kitano et al. estimated the short-term drop in transmission for Invasive pneumococcal disease to be 26% but highlight that overall burden would still increase due to service disruption in Japan.

Uncertainty is a key consideration and we have propagated uncertainty from inputs, through the parameter estimation, and through the model structure, to our outputs and estimates. There are some areas, however, where we have not included uncertainty: namely demography and vaccination data. Demography has wide-ranging implications for estimating vaccination coverage, campaign efficiency, and in how transmission is projected especially where population structure is expected to affect epidemiological contacts. We may also expect uncertainty to increase as we project into the future and over the course of the lifespans of individuals vaccinated. As a result, our estimates will substantially underestimate uncertainty from these factors and it is an area of intense research to understand the implications of demographic uncertainty on epidemiological modelling and vaccine impact.

As a result of COVID-19, the way immunisation itself is conducted has changed [45, 23] and this has increased costs by $0.32–0.85 per dose during campaigns [46]. In our study we have examined the short-term implications of coverage disruption; however, we may expect vaccination approaches themselves to

[1] eg. Bangladesh [15]; Haiti, Lesotho and Malawi [19]; Pakistan [25]; Canada [36, 37] or USA [30, 38, 39]

[2] such as in Brazil [16], South Africa [27], Liberia and Somalia [28], Canada [36, 37] or USA [30, 38, 39]

change over time as a result of the pandemic. This may be through combining activities with ongoing COVID-19 vaccination and mitigation efforts to reinforce health care systems, or, there may be negative implications of increased healthcare demand. The latter may have knock on effects with other vaccine introductions. COVID-19 is not the only recent vaccine to be considered in this way, malaria vaccination strategies may also have the same potential strengthening or delaying effects as it is included in activities for endemic regions. The complex interactions between vaccination schedules are an area of ongoing research and the implication of malaria and COVID-19 vaccination themselves will have far-reaching ramifications in both operational planning and in background mortality.

4 Conclusions

Our study is the first robust attempt to capture the impact of stagnation and disruption in coverage services on disease burden across multiple vaccines and Regions. We highlight the heterogeneity, the dramatic changes to expected progress, and the potential road to recovery in vaccine preventable disease control. Previous studies have highlighted the importance of sustained commitment and this is particularly emphasised here. We confirm a suspicion highlighted in other studies: that the ability to identify cohorts with higher an expected disease burden can help support catch-up activities. Yet, we have reason to be positive — there are still huge leaps in immunisation achieved and in planned vaccination activities. Additionally, new vaccine introductions such as COVID-19 or malaria, could strengthen existing schedules and improve focus on optimising vaccination activities.

5 Methods and data

5.1 Demographic data

All modelling groups in the VIMC are provided with standardised, national, age-desegregated demographic data based on the 2019 United Nations World Population Prospects (UNWPP). The 112 countries were chosen as they were either currently, or formerly, Gavi-supported or were subject to high burden and/or potential vaccine introduction. See Toor et al. for a full list of countries [7].

5.2 Vaccination coverage scenarios

The coverage scenarios depend on a number of data sources and align in timing with those used in the IA2030 projections [47]. The routine immunisation coverage relies on information from WUENIC up to 2020 (inclusive) [48]. We then examine whether there has been disruption due to COVID-19 by comparing 2019 and 2020 achieved coverage levels; if the 2020 levels are below those of 2019, we assume there is a linear recovery period whereby we reach pre-pandemic levels by 2022. If 2020 levels are equal to or greater than 2019, we assume scale-up begins immediately. Scale-up describes a nonlinear increase towards 2030 endpoints where the endpoints are conservative scaling of the IA2030 targets in line with operational forecasts. Campaign coverage is based on the WHO immunisation repository as of 31 Aug 2021 then follows guidance in terms of campaign frequency or aligning with vaccine introductions. A detailed description of data sources or assumptions by year and vaccine is given in table **??** and in section A.

5.3 Models

The current work presents results from all modelling groups currently in the VIMC. Each group provides projections of burden under various vaccination scenarios including: no-vaccination, routine-only and non-routine vaccination (as appropriate), where burden is defined as deaths cases or DALYs (disability adjusted life-years). The central secretariat then uses these estimates to calculate vaccine impact from various views, detailed in section 5.4. There are 21 groups included in the VIMC at present with two per disease area, excluding Hib. The aim of using two models per area is to include structural uncertainty in the resulting estimates. Model characteristics vary by group and vaccine from static to dynamic transmission models, full model details are available in section C.

Per disease area, each group was asked to provide 200 estimates of burden for each year, vaccination scenario and country. these varied by the sample of model parameters used. All vaccination scenarios were compared for the same set of model parameters. The mean and credible intervals were calculated by combining the full probabilistic distributions of impact for all models for a pathogen. When calculating the aggregated impact across pathogens, bootstrap sampling was used where a sample was taken from an individual model, averaged across models of the same pathogen and then summed across all pathogens. 1,000 bootstraps were used.

5.4 Impact calculations

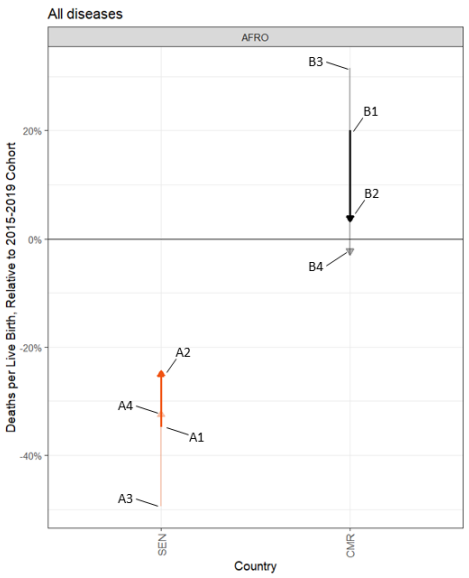
We calculate burden averted by vaccination in three views: by calendar year, birth cohort or year of vaccination stratified by activity type [49]. In order to calculate the latter, we estimate impact ratios which are burden averted per vaccinated individual and stratify them by vaccine activity, country and vaccine.

5.5 Number needed to vaccinate

Number needed to vaccinate (NNV) is a metric used to evaluate the public health benefit of immunisation programmes, calculated in this study as the number of FVPs from immunisation activities in a particular year per burden outcome averted (i.e. deaths, cases, or DALYs) [50]. We present the NNV from 2019-2024 stratified by disease and WHO Region. This can also be considered the converse of burden averted per FVP.

5.6 Expected vs. estimated decline in burden by cohort

In order to identify cohorts that may have been missed by interventions, and could now be beneficial targets for catch-up activities, we compare the expected vs. estimated burden in post-pandemic birth cohorts. Figure 8 shows a heuristic description of this method. We project the "expected" number of deaths per birth cohort in 2020-2024 under pre-COVID conditions by linearly extrapolating the estimates from the pre-pandemic birth cohorts in 2015-2019. We compare this expected burden to the modelled estimates for the 2020-2024 birth cohorts based on the latest data. Where the five-year pre-pandemic trend had been negative (i.e. the burden had been decreasing across successive birth cohorts), we can examine whether the trend continues, stagnates or reverses over the initial post-pandemic years. Where the pre-pandemic burden had been increasing over time, we can review whether the rate of increase accelerates over the post-pandemic years. Where the modelled burden is larger than the expected burden between 2020-2024, it may suggest cohorts who have fallen short of pre-COVID expectations and may be candidates for catch-up efforts.



- Across all 12 VPDs in Senegal (SEN):
  - For the 2020-2022 cohort (solid line):
    Assuming the linear trend in burden from 2015-2019 had continued, there would have been 35% fewer **(A1)** deaths per live birth in the 2020-2022 cohort than in the 2015-2019 cohort. The latest models estimate 25% fewer **(A2)** deaths per live birth in the 2020-2022 cohort than in the 2015-2019 cohort.
  - For the 2023-2024 cohort (transparent line):
    Assuming the linear trend in burden from 2015-2019 had continued, there would have been 48% fewer **(A3)** deaths per live birth in the 2023-2024 cohort compared to the 2015-2019 cohort. The latest models project 32% fewer **(A4)** deaths per live birth in the 2023-2024 cohort than in the 2015-2019 cohort.
  - The values **A2** and **A4** are negative, indicating the latest models estimate a reduction in burden in the post-COVID cohorts compared to the 2015-2019 cohort. However, the arrows are pointing up to show that estimated burdens (**A2** and **A4**) are higher than expected burdens under the pre-COVID linear trend assumption (**A1** and **A3**), and thus estimated progress in reducing burden has slowed post-COVID.
- Across all 12 VPDs in Cameroon (CMR):
  - For the 2020-2022 cohort (solid line):
    Assuming the linear trend in burden from 2015-2019 had continued, there would have been 20% more **(B1)** deaths per live birth in the 2020-2022 cohort than in the 2015-2019 cohort. The latest models estimate 5% fewer **(B2)** deaths per live birth in the 2020-2022 cohort than in the 2015-2019 cohort.
  - For the 2023-2024 cohort (transparent line):
    Assuming the linear trend in burden from 2015-2019 had continued, there would have been 32% more **(B3)** deaths per live birth in the 2023-2024 cohort compared to the 2015-2019 cohort. The latest models project 3% fewer **(B4)** deaths per live birth in the 2023-2024 cohort than in the 2015-2019 cohort.
  - The arrows are pointing down to show that estimated burdens (**B2** and **B4**) are lower than expected burdens under the pre-COVID linear trend assumption (**B1** and **B3**), and thus estimated progress in reducing burden has accelerated post-COVID.

Figure 8: Heuristic description of approach for estimating whether projected progress in reducing burdens has slowed in the 2020-2022 and 2023-2024 post-COVID cohorts, compared to the linear pre-COVID trend from 2015-2019

5.7 Meningitis A and Yellow Fever Elimination

'Defeating Menginitis by 2030' is a roadmap to further the global public health response to meningitis, by reducing cases of vaccine-preventable bacterial meningitis by 50% and deaths by 70%" [51]. Mean meningitis deaths were calculated for each WHO AFRO country through 2024, with a target value representing a 70% reduction in 2015 deaths to be achieved in 2030.

The "Eliminate Yellow Fever Epidemics 2017-2026" (EYE) strategy includes several key milestones, including (a) by 2022, at least 50% of the target population in high-risk countries in Africa has been protected through national preventative mass vaccination campaigns and (b) by 2026, all high-risk countries have completed national preventative mass vaccination campaigns [52]. Total FVPs for YF are shown from 2017-2026, in which the target value is calculated as 50% of the target population in 2022.

6 Author contributions

To be completed from the results of the google form https://forms.gle/6c8JXAQGHQC8Fan78

7 Declaration of interests

This work was carried out as part of the Vaccine Impact Modelling Consortium (VIMC, www.vaccineimpact.org). VIMC is jointly funded by Gavi, the Vaccine Alliance, and by the Bill Melinda Gates Foundation. The views expressed are those of the authors and not necessarily those of the Consortium or its funders. The

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8 Role of the funding source

The views expressed are those of the authors and not necessarily those of the Consortium or its funders. The funders were given the opportunity to review this paper prior to publication, but the final decision on the content of the publication was taken by the authors.

9 Data sharing agreement

All code and data is available at `github link to be added before submission`.

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