Health impact of routine immunisation service disruptions and mass vaccination campaign suspensions caused by the COVID-19 pandemic: Multimodel comparative analysis of disruption scenarios for measles, meningococcal A, and yellow fever vaccination in 10 low- and lower middle-income countries

Katy Gaythorpe¹*, Kaja Abbas²*, John Huber³*, Andromachi Karachaliou⁴*, Niket Thakkar⁵*, Kim Woodruff², Xiang Li², Susy Echeverria-Londono³, VIMC Working Group on COVID-19 Impact on Vaccine Preventable Disease, Matthew Ferrari⁶^, Michael L. Jackson⁷^, Kevin McCarthy⁵^, Alex Perkins³^, Caroline Trotter⁴^, Mark Jit²,8^, Matthew Ferrari²,8^, Michael L. Jackson⁷^, Kevin McCarthy⁵^, Alex Perkins³^, Caroline Trotter⁴^, Mark Jit²,8^

* equal contribution (first author)

^ equal contribution (senior author)

¹ MRC Centre for Global Infectious Disease Analysis, Abdul Latif Jameel Institute for Disease and Emergency Analytics (J-IDEA), School of Public Health, Imperial College London, London, United Kingdom

² Centre for Mathematical Modelling of Infectious Diseases, London School of Hygiene & Tropical Medicine, London, United Kingdom

³ Department of Biological Sciences, University of Notre Dame, South Bend, Indiana, United States of America

⁴ Department of Veterinary Medicine, University of Cambridge, Cambridge, United Kingdom

⁵ Institute for Disease Modeling, Bill & Melinda Gates Foundation, Seattle, Washington, United States of America

⁶ Pennsylvania State University, University Park, Pennsylvania, United States of America

⁷ Kaiser Permanente Washington, Seattle, Washington, United States of America

⁸ School of Public Health, University of Hong Kong, Hong Kong SAR, China

The following authors were part of the VIMC Working Group on COVID-19 Impact on Vaccine-Preventable Disease. Each contributed to processing, cleaning and/or interpretation of data, interpreted findings, contributed to the manuscript, and approved the work for publication: Andre Arsene Bita Fouda, Felicity Cutts, Emily Dansereau, Antoine Durupt, Ulla Griffiths, Jennifer Horton, Kendall Krause, Katrina Kretsinger, Tewodaj Mengistu, Imran Mirza, Simon R Procter, and Stephanie Shendale.

Corresponding author: Mark Jit, Faculty of Epidemiology and Population Health, London School of Hygiene & Tropical Medicine, Keppel Street, London WC1E 7HT, United Kingdom. Telephone: +44 (0)207 927 2852. Email: mark.jit@lshtm.ac.uk
Contributors

KG, KA, JH, AK, NT, KW, XL, SEL, MF, MLJ, KM, AP, CT and MJ verified the underlying data and conducted the simulations described in this paper. All authors including members of the VIMC Working Group on COVID-19 Impact on Vaccine-Preventable Disease contributed to interpreting the results, reviewing and editing of the manuscript and have approved the final version.

Declaration of interests

FC declares consultancy fees from the Bill & Melinda Gates Foundation (BMGF). CT declares a consultancy fee from GSK in 2018 (unrelated to the submitted work). ED and KKra are employees of the Bill & Melinda Gates Foundation, which funded the research. KM and NT are employees of the Institute for Disease Modeling at the Bill & Melinda Gates Foundation, which funded the research. TM is an employee of Gavi, which funded the research.

Funding and Acknowledgements

We would like to thank the following non-author collaborators: Jim Alexander, Laurence Alcyone Cibrelus Yamamoto, Natasha Crowcroft, Heather Ferguson, Neil Ferguson, James Goodson, Brittany Hagedorn, Lee Hampton, Lee Lee Ho, Dan Hogan, Raymond Hutubessy, Sudhir Khanal, Balcha Girma Masresha, Jonathan Mosser, Mark Papania, Bryan Patenaude, William Augusto Perea Caro, Robert Perry, Jeff Pituch, Allison Portnoy, Marie-Pierre Preziosi, Cassandra Quintanilla Angulo, Olivier Ronveaux, Sara Sa Silva, Yodit Sahlemariam, Alyssa Sbarra, Yoonie Sim, David Sniadack, Matthew Steele, Claudia Steulet, Peter Strebel, Aaron Wallace, Susan Wang, Xinhu Wang, Kirsten Ward, Libby Watts, and Karene Yeung.

This study was carried out as part of the Vaccine Impact Modelling Consortium, and funded by Gavi, the Vaccine Alliance and the Bill & Melinda Gates Foundation (OPP1157270 and INV-016832). This publication is based on research funded in part by the Bill & Melinda Gates Foundation, including but not limited to models and data analysis performed by the Institute for Disease Modeling at the Bill & Melinda Gates Foundation. The views expressed are those of the authors and not necessarily those of the Consortium or its funders.
Summary

Background: Childhood immunisation services have been disrupted by the COVID-19 pandemic. WHO recommends considering outbreak risk using epidemiological criteria when deciding whether to conduct preventive vaccination campaigns during the pandemic.

Methods: We used 2-3 models per infection to estimate the health impact of 50% reduced routine vaccination coverage in 2020 and delay of campaign vaccination from 2020 to 2021 for measles vaccination in Bangladesh, Chad, Ethiopia, Kenya, Nigeria, and South Sudan, for meningococcal A vaccination in Burkina Faso, Chad, Niger, and Nigeria, and for yellow fever vaccination in the Democratic Republic of Congo, Ghana, and Nigeria. Our counterfactual comparative scenario was sustaining immunisation services at coverage projections made prior to COVID-19 (i.e. without any disruption).

Findings: Reduced routine vaccination coverage in 2020 without catch-up vaccination may lead to an increase in measles and yellow fever disease burden in the modelled countries. Delaying planned campaigns in Ethiopia and Nigeria by a year may significantly increased the risk of measles outbreaks (both countries did complete their SIAS planned for 2020). For yellow fever vaccination, delay in campaigns leads to a potential disease burden rise of >1 death per 100,000 people until the campaigns are implemented. For meningococcal A vaccination, short term disruptions in 2020 are unlikely to have a significant impact due to the persistence of direct and indirect benefits from past introductory campaigns of the 1 to 29-year-old population, bolstered by inclusion of the vaccine into the routine immunisation schedule accompanied by further catch-up campaigns.

Interpretation: The impact of COVID-19-related disruption to vaccination programs varies between infections and countries. Planning and implementation of campaigns should consider country and infection-specific epidemiological factors and local immunity gaps worsened by the COVID-19 pandemic when prioritising vaccines and strategies for catch-up vaccination.

Funding: Bill & Melinda Gates Foundation and Gavi, the Vaccine Alliance
Research in context

Evidence before the study

We searched PubMed for (COVID-19 OR coronavirus OR SARS-CoV-2) AND (child health intervention OR vaccin* or immuni*) AND (disruption OR suspension OR reduction) AND (indirect effect OR health impact) on January 14, 2021, with no language restrictions. We found 178 articles of which 13 articles were relevant. Six articles reported some empirical data on immunization disruption in Bangladesh, Japan, Kenya, Nigeria, Pakistan, Saudi Arabia, South Africa, Spain and Italy, and a survey study focussed on immunization disruption in low and middle-income countries. One article proposed using the WHO health systems framework to assess the effects of COVID-19 on immunisation programmes in South Africa, another study on leveraging systems thinking and implementation science to improve immunization system performance in Africa, and two studies were review articles. One modelling study focused on the indirect effects, including reduction in routine immunisation services, of the COVID-19 pandemic on maternal and child mortality in low-income and middle-income countries. Another modelling study focused on a benefit-risk analysis of routine childhood immunisation during the COVID-19 pandemic in Africa. We also found one other study in the grey literature that analysed the impact on SARS-CoV-2 infections as a result of fixed-post and door-to-door vaccination campaigns targeted at children under five years of age in an Ethiopia-like setting.

Added value of this study

We estimated the increase in cases and deaths caused by the disruption to immunisation services leading to outbreaks for measles, meningococcal A and yellow fever in 10 countries. The reduction in routine immunisation coverage among under-immunised cohorts of children has enhanced the risk of outbreaks which cannot be averted without catch-up vaccination. This can lead to an increase of 9.89% (0.91 additional deaths per 100,000 individuals, or 48,000 in total) across the three diseases from 2020 to 2030 in the countries considered. Results vary by infection and country, but generally most excess deaths are due to measles. Postponing campaign immunisation may not have a detrimental short-term health impact if campaign immunisation is implemented ahead of future outbreaks caused by these immunity gaps.

Implications of the available evidence

The COVID-19 pandemic has caused significant disruptions to routine services and vaccination campaigns and resulted in immunity gaps with potential to cause outbreaks in the affected populations. The short-term and long-term health impact differ between measles, meningococcal A and yellow fever vaccination and by countries based on the local epidemiological situation. Thereby, catch-up vaccination should be planned by considering the heterogeneity in population susceptibility across different countries to measles, meningococcal A and yellow fever outbreaks and implemented in time to prevent these outbreaks. The study findings can inform risk-benefit trade-off discussions around the timing of campaigns.
Introduction

Childhood immunisation services have been disrupted by the COVID-19 pandemic in at least 68 countries during 2020 with around 80 million under-one-year-old children being affected.\textsuperscript{1–4} This has occurred for several reasons – the diversion of health care staff, facilities, and finances to deal with COVID-19 treatment and response; reluctance of individuals to bring children to be vaccinated due to fear of infection; barriers to travel due to local physical distancing measures; disruptions in vaccine supply chains; lack of personal protective equipment; and decisions to stop or postpone vaccination campaigns to reduce the risk of transmission during such campaigns.

The World Health Organization (WHO) issued guidance in March 2020 on immunisation activities during the COVID-19 pandemic.\textsuperscript{5} The guidance recommended a temporary suspension of mass vaccination campaigns, but continuation of routine immunisation services by the health systems while maintaining physical distancing and infection prevention and control measures for COVID-19. Routine immunisation was one of the most disrupted services relative to other essential health services based on a WHO pulse survey in May and June 2020 that was focused on continuity of essential health services during the COVID-19 pandemic.\textsuperscript{6} WHO, UNICEF, Gavi, the Vaccine Alliance, and their partners also conducted two pulse polls in April and June 2020 to understand COVID-19-related disruptions to immunisation services.\textsuperscript{7} Based on respondents from 82 countries, pulse polls indicated that there was widespread disruption to routine immunisation services in addition to the suspension of mass vaccination campaigns. The main reasons reported for this disruption were low availability of personal protection equipment for healthcare workers, low availability of health workers, and travel restrictions.

Disruptions to routine health care due to the COVID-19 pandemic are projected to increase child and maternal deaths in low-income and middle-income countries.\textsuperscript{8} No country has made a policy decision to stop routine immunisation during a COVID-19 epidemic. Risk-benefit analysis of countries in Africa shows routine immunisation to have far greater benefits than risks even in the context of the COVID-19 pandemic.\textsuperscript{9} Nevertheless, routine immunisation coverage has dropped in most countries.\textsuperscript{7}

Evidence on the health impact of suspending vaccination campaigns during the COVID-19 pandemic is limited. Modelling indicates that both fixed post and door-to-door campaigns targeting under 5-year-old children may cause temporary minor increases in total SARS-CoV-2 infections.\textsuperscript{10} However, avoiding campaigns during the local peak of SARS-CoV-2 transmission is key to reducing the effect size, and SARS-CoV-2 transmission during campaigns can be minimised with good personal protective equipment and limiting movement of vaccinators.\textsuperscript{10} The WHO recommends that countries consider the risk of outbreaks using epidemiological criteria when deciding whether to conduct preventive vaccination campaigns during the COVID-19 pandemic, but the guidance was not based on any quantitative assessment of transmission risk for either COVID-19 or existing vaccine-preventable diseases.\textsuperscript{11}
Hence, countries need to assess the health impact of postponing vaccination campaigns, which can inform the epidemiological risk assessment for outbreaks due to campaign delays and prioritise which vaccines to use in campaigns. The need for such assessments is greatest in low- and lower middle-income countries which generally have greater risks of vaccine-preventable disease outbreaks and limited health care resources to deal with COVID-19 epidemics. It is difficult to quantify the impact of different scenarios using only observational data, which does not give the counterfactual to what actually happened in 2020. To address this, we used transmission dynamic models to project alternative scenarios about postponing vaccination campaigns alongside disruption of routine immunisation, for three antigens with high outbreak potential and for which mass vaccination campaigns are a key delivery mode alongside routine immunisation – measles, meningococcal A, and yellow fever.
Methods

Deaths and disability-adjusted life years (DALYs) due to measles, meningococcal A and yellow fever under different routine and campaign vaccination scenarios were projected in a subset of 10 low- and lower middle-income countries over the years 2020-2030. Projections were made using previously validated transmission dynamic models; we used three models for measles, two models for meningococcal A, and two models for yellow fever. The results of the models were averaged using the arithmetic mean of their predictions for deaths and DALYs. Guidance used by the different models for DALY calculations are publicly accessible.\textsuperscript{13}

The chosen countries were low- and lower-middle-income countries that had planned vaccination campaigns in 2020 and were selected following consultations with partners in WHO, UNICEF, CDC and other organisations. Thereby, the selected countries differ between infections – Bangladesh, Chad, Ethiopia, Kenya, Nigeria, and South Sudan for measles; Burkina Faso, Chad, Niger, and Nigeria for meningococcal A; Democratic Republic of the Congo, Ghana, and Nigeria for yellow fever.

Models used routine and campaign vaccination coverage from WUENIC and post campaign surveys for 2000-2019,\textsuperscript{14} and future projections of routine coverage based on assumptions agreed with disease and immunisation programme experts at the global, regional, and national levels (see Table S11). We explored four scenarios that assumed different levels of disruption in the year 2020 to routine immunisation and postponement of campaigns projected in the scenarios, due to COVID-19 (see Table 2). The disruption scenarios are based on 50% reduction in routine immunisation and/or suspension of campaign vaccination in 2020 and postponement to 2021. These disruption scenarios aimed to approximate plausible drops in routine coverage levels and plausible delays to campaigns due to the COVID-19 pandemic.

We estimated the health impact of these disruption scenarios in comparison to the counterfactual scenario of no disruption (BAU – business-as-usual scenario) for measles, meningococcal A, and yellow fever during 2020-2030. We estimated the health impact of routine and campaign immunisation disruption through projections of total deaths (and DALYs) per 100,000 population, excess deaths (and DALYs) per 100,000 population, and excess deaths (and DALYs) during 2020-2030 which were scaled relative to the maximum number of excess deaths (or DALYs) across all scenarios. We did not assume any changes to case-fatality risks as a result of the COVID-19 pandemic.

Role of the funding source

The funders were involved in study design, data collection, data analysis, data interpretation, writing of the report, and the decision to submit for publication. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.
Ethical considerations

This analysis used only data in the public domain or projections based on assumptions from programme managers.
Results

The health impact varies across the disruption scenarios for the three infections in the different countries. Figure 1 shows the average model predicted total deaths per 100,000 population per year during 2020-2030 (see Figure S1 for similar projections for DALYs impact, Tables 3 and S1 for scenario averages over the entire time period, and Table S3-S11 for absolute numbers of deaths).

In the case of measles, Bangladesh initially postponed its campaign by a few months; models suggest that this does not lead to increased risk of outbreaks but a reduction in routine immunisation coverage in 2020 leads to increased risk of outbreaks during 2028-2030. This leads to an average increase in deaths per 100,000 of 0.015 for 2020 - 2030 when the campaign is delayed, but an average increase of 0.16 if routine coverage drops. For Ethiopia, the postponement of immunisation campaigns from 2020 to 2021 would have led to increased risk of outbreaks in 2020 while a reduction in routine immunisation coverage in 2020 would not lead to increased risk of outbreaks in 2020. Overall this equates to an average increase of 2.26 deaths per 100,000 in 2030-2030 for a drop in routine coverage and an increase of 1.78 if the campaign is delayed. The Ethiopian campaign was eventually reinstated only three months later than scheduled, following consideration of these findings. For Kenya, the disruption to routine and campaign immunisation would not lead to increased risk of outbreaks, due to high coverage of the first dose of measles vaccine and better optimally-timed campaigns in preventing outbreaks during 2020-2030 though coverage of the second-dose of measles vaccine is sub-optimal.

For Nigeria, the postponement of immunisation campaigns from 2020 to 2021 would not impact the risk of the next projected outbreak in 2025, while a reduction in routine immunisation coverage in 2020 brings forward the risk of the next projected outbreak from 2025 to 2023. Over 2020 - 2030 this leads to an increase in deaths per 100,000 of 0.23 when routine coverage drops and 0.10 when campaigns are delayed. For South Sudan, the postponement of immunisation campaigns from 2020 to 2021 would be beneficial in averting a potential outbreak in 2022 leading to a reduction in deaths per 100,000 of 3.84 over 2020-2030. For Chad, the postponement of immunisation campaigns from 2020 to 2021 would lead to increased risk of outbreaks in 2020 while a reduction in routine immunisation coverage in 2020 without catch-up may bring forward the risk of the next projected outbreak from 2023 to 2022. However, overall the average deaths per 100,000 may increase by 1.24 from 2020-2030 if routine coverage drops and decreases by 1.01 if a campaign is delayed. Model-specific estimates of measles deaths per 100,000 per country are provided in Table S2 with absolute numbers for all countries per model given in Table S11.

In the case of meningococcal A (MenA), the short-term disruption to routine immunisation in Burkina Faso, Niger, Nigeria and Chad, as well as the short-term disruption of immunisation campaigns in Nigeria and Chad would not have a significant impact on the disease incidence, see Table S4 for model-specific estimates by country. These four countries conducted mass preventive campaigns targeting 1-29-year-old populations between 2010 and 2014, and introduced the vaccine
into their routine immunization schedules between 2016 and 2019. Niger and Burkina Faso completed catch-up campaigns concomitantly with the introduction into routine, and Chad and Nigeria have started but not completed their catch-up campaigns. A maximum of a 4% increase in MenA deaths over the long term is projected and with minimal change in the short term of within 5 years. This is because of the persistence of protection against MenA due to the vaccination strategy combining mass vaccination campaign and routine introduction, which led to a lasting interruption of transmission, in particular from the direct and indirect effects of the initial mass campaigns of the 1-29-year-old population in 2010-2014.

In the case of yellow fever, for the Democratic Republic of Congo and Nigeria, the postponement of immunisation campaigns from 2020 to 2021 was predicted to cause a short-term increase in burden but when campaigns were implemented, the overall burden was reduced for the time period. A reduction in routine immunization during 2020 was predicted to increase burden over the same period 2020-2030. For Ghana, the postponement of immunisation campaigns from 2020 to 2021 does not increase the yellow fever burden in the short-term, whereas a reduction in routine immunization in 2020 increases the yellow fever burden by, on average, 0.2 deaths per 100,000 between 2020 and 2030. Model-specific estimates of excess deaths by country from 2020 to 2030 are shown in Table S6. Neither model was designed to specifically capture yellow fever outbreak dynamics. Therefore, although the delay of immunisation campaigns was predicted to reduce the burden of yellow fever for 2020-2030 in select settings by a small (less than 1%) amount, the increased risk of an outbreak is not accounted for in the models and this could outweigh the predicted long-term benefits.

Figure 2 shows the average model predicted excess deaths per 100,000 population per year for routine and campaign immunisation disruption scenarios in comparison to no disruption scenario for measles, meningococcal A, and yellow fever. The excess deaths are summed over 2020-2030 (see Figure S2 for similar projections for DALYs impact). The scale of excess mortality due to the immunisation service disruptions are higher for measles vaccination in comparison to meningococcal A and yellow fever vaccination; indeed excess mortality is minimal for meningococcal A.

Figure S3 shows the normalised average model predicted excess deaths per year and country for routine and campaign immunisation disruption scenarios in comparison to no disruption scenario for measles, meningococcal A, and yellow fever, and the excess deaths are summed and normalised over 2020-2030 (see Figure S4 for similar projections for DALYs impact). For measles, a 50% reduction in routine immunisation is projected to increase the excess deaths the most in comparison to scenarios involving the postponement of immunisation campaigns from 2020 to 2021 for Bangladesh, Chad and South Sudan and (with a delay to campaigns) in Nigeria. For MenA, a 50% reduction in routine immunisation and the postponement of immunisation campaigns from 2020 to 2021 is projected to increase the excess deaths the most for Chad, though the scale of absolute impact is minimal (see Figure 2). For yellow fever, a reduction in routine immunisation is projected to increase the excess deaths the most (either in conjunction with campaign delay or not).
the postponement of immunisation campaigns from 2020 to 2021 appears to have a beneficial impact of lower deaths in comparison to immunisation campaigns in 2020 for the Democratic Republic of the Congo in Figure S3, this does not capture the short-term increase in burden due to the missed campaign. The beneficial effect is due solely to the proportionally larger campaign implemented in 2021, that is a campaign with the same coverage leads to more fully vaccinated persons as the population grows.
**Discussion**

The health impact of routine immunisation service disruptions and mass vaccination campaign suspensions due to the COVID-19 pandemic differs widely between infections and countries, so decision-makers need to consider their local epidemiological situation. For meningococcal A and yellow fever, we predict that postponing campaigns has a minimal short-term effect because both pathogens have a low effective reproduction number and strong existing herd immunity from recent campaigns in the countries modelled (see Table S17). However, this is influenced by the model structures and their propensity to capture outbreak dynamics, which particularly affects the predictions for yellow fever. For measles, in some countries such as Ethiopia and Nigeria, even a one-year postponement of immunisation campaigns could have led to large outbreaks, but both countries were able to implement planned SIAs in 2020 after a few months’ delay. In other countries with high routine immunisation coverage and/or recent campaigns, SIAs may be postponed by a year without causing large outbreaks.

In some of our modelled scenarios, postponement of immunisation campaigns does not appear to increase overall cases, if the delay time-period is less than the interval to the next outbreak. Such a scenario is inferred in the immunisation disruption scenarios for postponement of measles campaigns for South Sudan. This does not imply that a postponement is preferred, as we do not take into account other contextual or programmatic factors; rather it reflects the effectiveness of campaigns in closing the immunity gaps and the demographic effect of including more children in delayed campaigns. In instances with very low routine immunisation coverage, there is possibility that the vaccination campaign is the main opportunity for missed children to be vaccinated. Thus for the same proportion of the same age group targeted by campaigns, more children will be vaccinated for the same coverage levels in countries with birth rates increasing over time. While these results may be useful in the COVID-19 context, there is also considerable uncertainty around both model findings and data inputs such as incidence and vaccine coverage that prohibits further general comment on the optimal timing of campaigns.

The measles immunisation campaigns for 2020 in Nigeria were specifically targeted at Kogi and Niger states that were originally scheduled for inclusion in the campaigns for 2019 across northern Nigeria but were delayed for other reasons. These campaigns were implemented in October 2020. Given the localised nature of susceptibility and targeted campaigns specifically to these two states to address the low routine immunisation coverage and the long window between campaigns, there is a high risk of localised outbreaks in these two states in 2021. In general, for countries where routine immunization coverage was low even before the COVID-19 pandemic, the build-up of the susceptible population from low routine immunisation coverage over two to three years between campaigns enhances the risk of outbreaks more than recent and temporary disruptions to routine immunisation. Further, our models did not include the possibility that COVID-19 restrictions may have temporarily reduced measles transmissibility and the risk of measles outbreaks due to reduced chance of introduction of infection into populations with immunity gaps. This risk rises again rapidly.
once travel restrictions and physical distancing are relaxed, thereby underlying the significance of implementing postponed immunisation campaigns at the earliest to prevent measles outbreaks as COVID-19 restrictions are lifted.15

While the degree of health impact of service disruptions varies, the average models show that reductions in routine immunization coverage have a far greater impact on predicted excess deaths over the next decade for all infections modeled than postponement of campaigns. This has significant implications for countries planning catch-up strategies and highlights the need for increased emphasis on the importance of implementing catch-up as an ongoing part of routine immunization.12

The disease burden averted by measles and meningococcal A vaccination are primarily among under-5-year-old and under-10-year-old children respectively, and disease burden averted by yellow fever vaccination are among younger age-group individuals. Since children and younger age-group individuals are at relatively lower risk of morbidity and mortality from COVID-19 in comparison to elderly population, the health benefits of sustaining measles, meningococcal A, and yellow fever immunisation programmes during the COVID-19 pandemic outweighs the excess SARS-CoV-2 infection risk associated with vaccination service delivery points. Thereby, the delivery of measles, meningococcal A, and yellow fever immunisation services should continue, as logistically as possible, by adapting service delivery in a COVID-secure manner with implementation of SARS-CoV-2 infection prevention and control measures.

Our study has limitations and we have not considered logistical constraints posed by the COVID-19 prevention and control measures on vaccine supply, demand for vaccination, access, and health workforce. Future introduction of COVID-19 vaccination may also divert the workforce normally conducting campaigns for other vaccines. Our models do not reflect geographical heterogeneity sub-nationally, whereas in reality this is a key feature. Nor do we incorporate known seasonality of infections, which may affect the window of opportunity for catching up. The models used in this analysis, in particular for yellow fever, are best suited to capture long-term changes in disease burden due to vaccination and cannot capture outbreak dynamics that may arise in the short-term. A key strength of our analysis is that we used 2-3 models for each infection, which allowed investigation of whether projections were sensitive to model structure and assumptions. We did indeed find quantitative differences between models of the same infection, but most models agreed on the countries in which disruptions had the largest effect on disease burden.

We conducted our health impact assessment to align with the WHO framework for decision making using an evidence-based approach to assist in prioritisation of vaccines and strategies for catch-up vaccination during the COVID-19 pandemic.12 The framework highlights three main steps, with the primary step being an epidemiological risk assessment for each disease based on the burden of disease and population immunity, as well as the risk factors associated with the immunisation service disruptions. The second step focuses on the amenability of delivery strategies and
operational factors for each vaccine, and the third step on the assessment of contextual factors and competing needs.

Our health impact assessment addresses in part the primary step of an epidemiological risk assessment by estimating the disease burden for different immunisation scenarios, but does not include the health impact assessment of excess COVID-19 disease burden attributable to these immunisation scenarios. While we have assessed the immunity gaps caused by immunisation service disruptions for measles, meningococcal A, and yellow fever vaccination in 10 low- and lower middle-income countries, sustaining routine immunisation and resuming immunisation campaigns during the COVID-19 pandemic requires adaptations to service delivery with additional safety measures to protect the health workers and the community from SARS-CoV-2 infection. Infection prevention and control measures include personal protective equipment for health workers and children to be vaccinated and their parents or caregivers, additional prevention and control measures against SARS-CoV-2 infection at vaccination sites, physical distancing, and symptomatic screening and triaging. COVID-19 transmission may be further mitigated by delivering several vaccines during a single campaign (such as measles and polio vaccines), or even combining vaccines with other age-relevant interventions such as nutritional supplements. Further, social mobilisation is needed to address the rumours, misinformation, and fear among the community to access vaccination safely during the COVID-19 pandemic. Therefore, our health impact assessment needs to be followed up by planning and implementation of catch-up vaccination to close the immunity gaps using a mixture of locally-appropriate strategies to strengthen immunisation, alongside access to additional operating costs to conduct routine and campaign immunisation services safely in COVID-secure environments while considering contextual factors and competing needs.
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Tables

Table 1. Vaccine impact models. Summary characteristics of the transmission dynamic vaccine impact models for measles (three models), meningococcal A (two models), and yellow fever (two models).

| Infection       | Measles | Measles | Measles | MenA | MenA | Yellow fever | Yellow fever |
|-----------------|---------|---------|---------|------|------|--------------|--------------|
| Model name      | Penn State | DynaMICE | IDM | Cambridge | KP | Imperial | Notre Dame |
| Reference       | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Structure       | Semi-mechanistic | Compartmental | Compartmental | Compartmental | Compartmental | Semi-mechanistic | Semi-mechanistic |
| Randomness      | Stochastic | Deterministic | Stochastic | Stochastic | Stochastic | Deterministic | Deterministic |
| Time step       | Annual | Weekly | Semi-monthly | Daily | Weekly | Annual | Annual |
| Age stratification | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Model fitting   | Fitted to observed annual WHO case data (1980-2017) | Not fitted; uses country-specific $R_0$ (basic reproduction number) for measles from fitted models | Fitted to observed monthly WHO case data (2011-2019) | Not fitted; calibrated by comparing the predictions to evidence on carriage prevalence by age, disease incidence by age, total annual incidence, seasonality and periodicity | Fitted to carriage prevalence and disease incidence data for Burkina Faso; calibrated for other regions by comparing seasonality and incidence by age to disease surveillance data | Bayesian framework fitted to occurrence and serology data | Bayesian framework fitted to incidence and serology data |
| Case importations | Random | None | None | None | Infectious people immigrate at a rate of 0.1 - 1 per million population per week | Random | None |
|-------------------|--------|------|------|------|---------------------------------------------------------------------------------------------------------------------------------|--------|------|
| Dose dependenc y  | Second dose (MCV2) more likely to be given to those who received first dose (MCV1). SIA doses assumed to be independent from MCV1/2 | SIA doses are weakly dependent of MCV1/2 based on Portnoy et al.\textsuperscript{26} | No correlation between the two routine doses or between the routine and SIA doses | Not applicable since 2020 campaigns are targeting population missed by the introductory campaign who are too old for routine immunisation | Campaigns preferentially target unvaccinated persons | Random | Random |
| Countries modelled | Bangladesh, Chad, Ethiopia, Kenya, Nigeria, South Sudan | Ethiopia, Nigeria | Burkina Faso, Chad, Niger, Nigeria | Democratic Republic of the Congo, Ghana, Nigeria |

\textsuperscript{26}Portnoy et al.
Table 2: Immunisation scenarios. Scenarios for disruption of routine immunisation and delay of mass vaccination campaigns due to the COVID-19 pandemic for measles vaccination in 6 countries, meningococcal A vaccination in 4 countries, and yellow fever vaccination in 5 countries. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Immunisation scenario        | Routine immunisation (RI) | Campaign immunisation / Supplementary immunisation activities (SIAs) |
|------------------------------|----------------------------|---------------------------------------------------------------------|
| BAU                          | No disruption              | No disruption                                                       |
| Postpone 2020 SIAs -> 2021  | No disruption              | Postpone 2020 SIAs to 2021                                         |
| 50% RI                       | 50% reduction on RI for 2020 | No disruption                                                       |
| 50% RI, postpone 2020 SIAs -> 2021 | 50% reduction on RI for 2020 | Postpone 2020 SIAs to 2021 |

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Table 3: Average excess deaths per 100,000 between 2020-2030 per scenario, infection and modelling group. Scenarios for disruption of routine immunisation and delay of mass vaccination campaigns due to the COVID-19 pandemic for measles vaccination in 6 countries, meningococcal A vaccination in 4 countries, and yellow fever vaccination in 3 countries. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation. The total of pathogen averages is the sum of the average excess deaths per 100,000 for each pathogen.

| Scenario                          | Measles, DynaMICE | Measles, IDM | Measles, Penn State | Men A, Cambridge | Men A, KP | Yellow fever, Imperial | Yellow fever, Notre Dame | Total of pathogen averages |
|----------------------------------|-------------------|-------------|--------------------|------------------|----------|------------------------|-------------------------|---------------------------|
| 50% RI                           | 1.1569            | 1.1873      | 0.0501             | 0.0020           | 0.0001   | 0.1474                 | 0.0755                  | 0.9105                    |
| Postpone 2020 SIAs -> 2021       | 0.9428            | 0.1248      | -0.0104            | 0.0042           | -0.0001  | -0.0584                | -0.0103                 | 0.3202                    |
| 50% RI, postpone 2020 SIAs -> 2021| 0.2401            | 1.3134      | 0.0222             | 0.0064           | 0.0000   | 0.0876                 | 0.0536                  | 0.5990                    |
**Figures**

**Figure 1: Health impact of predicted total deaths for immunisation disruption scenarios and no disruption scenario for measles, meningococcal A, and yellow fever.** The average model predicted total deaths per 100,000 population per year for routine and campaign immunisation disruption scenarios and no disruption scenario (BAU – business-as-usual scenario) for measles, meningococcal A, and yellow fever during 2020-2030. The grey ribbon indicates the most extreme model estimates for all scenarios, that is for infections with two models – these lines indicate maximum and minimum model projections for all scenarios; the thick line indicates mean model projection.
Figure 2: Health impact of excess deaths for immunisation disruption scenarios in comparison to no disruption scenario for measles, meningococcal A, and yellow fever. The average model predicted excess deaths per 100,000 population per year for routine and campaign immunisation disruption scenarios in comparison to no disruption scenario (BAU – business-as-usual scenario) for measles, meningococcal A, and yellow fever. Excess deaths are summed over 2020-2030, and the error bars indicate the range in model projections.
Supplementary appendix

Tables (appendix)

Table S1: Average excess DALYs per 100,000 between 2020-2030 per scenario, infection and modelling group. Scenarios for disruption of routine immunisation and delay of mass vaccination campaigns due to the COVID-19 pandemic for measles vaccination in 6 countries, meningococcal A vaccination in 4 countries, and yellow fever vaccination in 3 countries. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Scenario                          | Measles, DynaMICE | Measles, IDM | Measles, Penn State | Men A, Cambridge | Men A, KP | Yellow fever, Imperial | Yellow fever, Notre Dame |
|----------------------------------|------------------|-------------|-------------------|----------------|-----------|-----------------------|-------------------------|
| 50% RI                           | 79.2110          | 68.5537     | 2.7503            | 0.1175         | 0.0037    | 9.3283                | 4.3831                  |
| Postpone 2020 SIAs → 2021        | 69.9709          | 5.7308      | -0.0990           | 0.2650         | -0.0027   | -2.7355               | -0.5797                 |
| 50% RI, postpone 2020 SIAs → 2021 | 17.0570          | 74.0683     | 1.6898            | 0.4017         | 0.0004    | 6.5284                | 3.1370                  |
Table S2: Average excess measles deaths per 100,000 between 2020-2030 per scenario, country and modelling group. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Country | 50% RI, DynaMIC E | 50% RI, Penn State | 50% RI, IDM | Postpone 2020 SIAs -> 2021, DynaMIC E | Postpone 2020 SIAs -> 2021, Penn State | Postpone 2020 SIAs -> 2021, IDM | 50% RI, postpone 2020 SIAs -> 2021, DynaMIC E | 50% RI, postpone 2020 SIAs -> 2021, Penn State |
|---------|-------------------|-------------------|------------|----------------------------------------|----------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| BGD     | 0.35              | -0.03             | NA         | 0                                      | 0.03                                   | NA                              | 0.03                            | 0.01                            |
| ETH     | 4.67              | 0                 | 2.1        | 5.56                                   | -0.03                                  | -0.19                           | 2.05                            | -0.07                           | 1.82                           |
| KEN     | 0                 | -0.01             | NA         | 0                                      | 0.01                                   | NA                              | 0                               | 0.01                            | NA                             |
| NGA     | -0.12             | 0.15              | 0.68       | -0.02                                  | 0.01                                   | 0.3                             | -0.09                           | 0.13                            | 1.03                           |
| SSD     | 3.28              | 0.03              | NA         | -6.73                                  | -0.95                                  | NA                              | -7.65                           | -0.96                           | NA                             |
| TCD     | 2.45              | 0.02              | NA         | -2.13                                  | 0.12                                   | NA                              | -0.16                           | 0.01                            | NA                             |
Table S3: Average excess measles deaths between 2020-2030 per scenario, country and modelling group. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Country | 50% RI, DynamiCE | 50% RI, Penn State | Postpone 2020 SIAs -> 2021, DynamiCE | Postpone 2020 SIAs -> 2021, IDM | Postpone 2020 SIAs -> 2021, DynamiCE | 50% RI, postpone 2020 SIAs -> 2021, Penn State | 50% RI, postpone 2020 SIAs -> 2021, IDM |
|---------|------------------|--------------------|-------------------------------------|---------------------------------|-------------------------------------|---------------------------------------------|---------------------------------------------|
| BGD     | 6552             | -539               | NA                                  | 0                              | 593                                 | NA                                          | 578                                         | 276                                         | NA                                          |
| ETH     | 66678            | 40                 | 29951                               | 79384                          | -473                                | -2783                                       | 29241                                      | -946                                        | 25981                                       |
| KEN     | 0                | -40                | NA                                  | 0                              | 64                                  | NA                                          | 0                                          | 59                                         | NA                                          |
| NGA     | -3016            | 3919               | 17545                               | -634                           | 137                                 | 7777                                        | -2430                                      | 3427                                        | 26559                                       |
| SSD     | 4493             | 44                 | NA                                  | -9229                          | -1298                               | NA                                          | -10485                                     | -1316                                       | NA                                          |
| TCD     | 5125             | 35                 | NA                                  | -4460                          | 260                                 | NA                                          | -333                                       | 29                                          | NA                                          |
Table S4: Average excess meningococcal A deaths per 100,000 between 2020-2030 per scenario, country and modelling group. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Country | 50% RI, Cambridge | 50% RI, KP | Postpone 2020 SIAs -> 2021, Cambridge | Postpone 2020 SIAs -> 2021, KP | 50% RI, postpone 2020 SIAs -> 2021, Cambridge | 50% RI, postpone 2020 SIAs -> 2021, KP |
|---------|------------------|-----------|-----------------------------------------|-------------------------------|---------------------------------------------|-------------------------------|
| BFA     | 0                | 0         | 0                                       | 0                             | 0                                           | 0                             |
| NER     | 0                | 0         | 0                                       | 0                             | 0                                           | 0                             |
| NGA     | 0                | 0         | 0                                       | 0                             | 0                                           | 0                             |
| TCD     | 0.02             | 0         | 0.07                                    | 0                             | 0.1                                         | 0                             |
Table S5: Average excess meningococcal A deaths between 2020-2030 per scenario, country and modelling group. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Country | 50% RI, Cambridge | 50% RI, KP | Postpone 2020 SIAs -> 2021, Cambridge | Postpone 2020 SIAs -> 2021, KP | 50% RI, postpone 2020 SIAs -> 2021, Cambridge | 50% RI, postpone 2020 SIAs -> 2021, KP |
|---------|------------------|-----------|-----------------------------------|-------------------------------|---------------------------------|-------------------|
| BFA     | 0                | 1         | 0                                 | 0                            | 0                               | 1                 |
| NER     | 14               | 0         | 0                                 | 0                            | 14                              | 0                 |
| NGA     | 0                | 0         | 0                                 | -2                           | 0                               | -1                |
| TCD     | 52               | 0         | 142                               | 0                            | 201                             | 0                 |
Table S6: Average excess yellow fever deaths per 100,000 between 2020-2030 per scenario, country and modelling group. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Country | 50% RI, Imperial | 50% RI, Notre Dame | Postpone 2020 SIAs -> 2021, Imperial | Postpone 2020 SIAs -> 2021, Notre Dame | 50% RI, postpone 2020 SIAs -> 2021, Imperial | 50% RI, postpone 2020 SIAs -> 2021, Notre Dame |
|---------|-----------------|-------------------|--------------------------|---------------------------------|----------------------------------|----------------------------------|
| COD     | 0.38            | 0.01              | -0.23                    | -0.01                           | 0.15                             | 0                                |
| GHA     | 0.33            | 0.07              | 0.06                     | 0.02                            | 0.39                             | 0.1                              |
| NGA     | 0.02            | 0.1               | 0                        | -0.02                           | 0.01                             | 0.07                             |
Table S7: Average excess yellow fever deaths between 2020-2030 per scenario, country and modelling group. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Country | 50% RI, Imperial | 50% RI, Notre Dame | Postpone 2020 SIAs -> 2021, Imperial | Postpone 2020 SIAs -> 2021, Notre Dame | 50% RI, postpone 2020 SIAs -> 2021, Imperial | 50% RI, postpone 2020 SIAs -> 2021, Notre Dame |
|---------|------------------|-------------------|-------------------------------------|-----------------------------------------|---------------------------------------------|---------------------------------------------|
| COD     | 4379             | 137               | -2590                               | -88                                     | 1731                                        | 25                                         |
| GHA     | 1241             | 281               | 239                                 | 94                                      | 1481                                        | 375                                        |
| NGA     | 421              | 2675              | -45                                 | -426                                    | 377                                         | 1798                                       |
Table S8: Average excess measles deaths per 100,000 between 2020-2030 per scenario, year and modelling group. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Year     | 50% RI, DynaMI CE | 50% RI, IDM | 50% RI, Penn State | Postpon e 2020 SIAs -> 2021, DynaMI CE | Postpon e 2020 SIAs -> 2021, IDM | Postpon e 2020 SIAs -> 2021, Penn State | 50% RI, postpon e 2020 SIAs -> 2021, DynaMI CE | 50% RI, postpon e 2020 SIAs -> 2021, IDM | 50% RI, postpon e 2020 SIAs -> 2021, Penn State |
|----------|-------------------|-------------|-------------------|------------------------------------------|----------------------------------|------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 2020     | 0                 | 0.34        | 0.06              | 10.46                                    | 2.32                             | 0.7                                      | 10.46                                         | 3.25                                          | 0.82                                          |
| 2021     | 0                 | 2.7         | 0.55              | 0.19                                     | 8.32                             | 0.02                                     | 0.2                                          | 13.55                                         | 0.44                                          |
| 2022     | 3.44              | 4.98        | 0                 | -2.52                                    | -1.27                            | -0.19                                    | -2.52                                         | 0.77                                          | -0.2                                          |
| 2023     | 28.56             | 6.57        | 0                 | -6.31                                    | -5.48                            | -0.1                                      | 4.96                                         | -0.96                                         | -0.12                                         |
| 2024     | -11.77            | 0.72        | -0.03             | -14.68                                   | -4.5                             | -0.12                                    | 5.96                                         | -2.48                                         | -0.16                                         |
| 2025     | -9.82             | -1.52       | 0.02              | 16.07                                    | 0.67                             | -0.1                                     | -14.65                                        | 0.03                                          | -0.13                                         |
| 2026     | -5.38             | -0.26       | 0.01              | -7.57                                    | 1.83                             | -0.1                                     | -3.38                                        | 1.51                                          | -0.11                                         |
| 2027     | 0.24              | 0.23        | 0.02              | 0.37                                     | 0.36                             | -0.03                                    | 1.08                                         | 0.6                                           | -0.04                                         |
| 2028     | 0.79              | 0.08        | 0                 | 0.88                                     | -0.02                            | -0.03                                    | -0.02                                         | 0.01                                          | -0.05                                         |
| 2029     | 0.55              | 0.09        | -0.02             | -0.3                                     | -0.03                            | -0.05                                    | 0.15                                         | -0.16                                         | -0.06                                         |
| 2030     | 6.55              | 0.09        | 0                 | 12.95                                    | -0.26                            | -0.04                                    | 1.45                                         | -0.1                                          | -0.05                                         |
Table S9: Average excess meningococcal A deaths per 100,000 between 2020-2030 per scenario, year and modelling group. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Year  | 50% RI, Cambridge | 50% RI, KP | Postpone 2020 SIAs -> 2021, Cambridge | Postpone 2020 SIAs -> 2021, KP | 50% RI, postpone 2020 SIAs -> 2021, Cambridge | 50% RI, postpone 2020 SIAs -> 2021, KP |
|-------|------------------|-----------|----------------------------------------|--------------------------------|---------------------------------|---------------------------------|
| 2020  | 0                | 0         | 0                                      | 0                              | 0                               | 0                               |
| 2021  | 0                | 0         | 0                                      | 0                              | 0                               | 0                               |
| 2022  | 0                | 0         | 0                                      | 0                              | 0                               | 0                               |
| 2023  | 0                | 0         | 0                                      | 0                              | 0                               | 0                               |
| 2024  | 0                | 0         | 0.01                                   | 0                              | 0.01                            | 0                               |
| 2025  | 0                | 0         | 0                                      | 0                              | 0                               | 0                               |
| 2026  | 0                | 0         | 0                                      | 0                              | 0                               | 0                               |
| 2027  | 0                | 0         | 0.01                                   | 0                              | 0.01                            | 0                               |
| 2028  | 0                | 0         | 0.01                                   | 0                              | 0.02                            | 0                               |
| 2029  | 0                | 0         | 0                                      | 0                              | 0                               | 0                               |
| 2030  | 0.01             | 0         | 0.01                                   | 0                              | 0.03                            | 0                               |
Table S10: Average excess yellow fever deaths per 100,000 between 2020-2030 per scenario, year and modelling group. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Year | 50% RI, Imperial | 50% RI, Notre Dame | Postpone 2020 SIAs -> 2021, Imperial | Postpone 2020 SIAs -> 2021, Notre Dame | 50% RI, postpone 2020 SIAs -> 2021, Imperial | 50% RI, postpone 2020 SIAs -> 2021, Notre Dame |
|------|-----------------|-------------------|-------------------------------------|---------------------------------------|------------------------------------------|-----------------------------------------------|
| 2020 | 0.28            | 0.12              | 1.7                                 | 0                                     | 2.02                                    | 0.12                                          |
| 2021 | 0.22            | 0.12              | -0.36                               | 0.86                                  | -0.15                                   | 0.98                                          |
| 2022 | 0.18            | 0.09              | -0.29                               | -0.14                                 | -0.12                                   | -0.07                                         |
| 2023 | 0.16            | 0.08              | -0.25                               | -0.12                                 | -0.1                                    | -0.05                                         |
| 2024 | 0.13            | 0.07              | -0.2                                | -0.1                                  | -0.07                                   | -0.04                                         |
| 2025 | 0.13            | 0.07              | -0.19                               | -0.09                                 | -0.07                                   | -0.04                                         |
| 2026 | 0.12            | 0.06              | -0.18                               | -0.09                                 | -0.07                                   | -0.04                                         |
| 2027 | 0.12            | 0.06              | -0.18                               | -0.09                                 | -0.06                                   | -0.04                                         |
| 2028 | 0.11            | 0.06              | -0.17                               | -0.09                                 | -0.06                                   | -0.04                                         |
| 2029 | 0.11            | 0.06              | -0.16                               | -0.08                                 | -0.06                                   | -0.04                                         |
| 2030 | 0.11            | 0.06              | -0.16                               | -0.08                                 | -0.06                                   | -0.04                                         |
Table S11: Average excess deaths between 2020-2030 per scenario, infection and modelling group.

Scenarios for disruption of routine immunisation and delay of mass vaccination campaigns due to the COVID-19 pandemic for measles vaccination in 6 countries, meningococcal A vaccination in 4 countries, and yellow fever vaccination in 3 countries. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Scenario                      | Measles, DynaMIC E | Measles, IDM\(^a\) | Measles, Penn State | Men A, Cambridge | Men A, KP | Yellow fever, Imperial | Yellow fever, Notre Dame | Total of pathogen averages\(^b\) |
|-------------------------------|--------------------|--------------------|---------------------|------------------|-----------|------------------------|--------------------------|---------------------------------|
| 50% RI                        | 79832.13           | 47495.71           | 3459.278            | 66               | 2.174381  | 6042.15                | 3093.147                 | 68265.66                       |
| Postpone 2020 SIAs -> 2021   | 65061.76           | 4994.18            | -715.324            | 142              | -1.78694  | -2395.67               | -420.914                 | 33689.78                       |
| 50% RI, postpone 2020 SIAs -> 2021 | 16570.58         | 52540.42           | 1529.764            | 215              | 0.06521   | 3589.54                | 2197.85                  | 37556.73                       |

\(^a\) Measles IDM covers only two countries.

\(^b\) Total of pathogen averages exclude Measles IDM as this covers only two countries.
Table S12: Percentage differences in deaths from baseline between 2020-2030 per scenario, infection and modelling group. Scenarios for disruption of routine immunisation and delay of mass vaccination campaigns due to the COVID-19 pandemic for measles vaccination in 6 countries, meningococcal A vaccination in 4 countries, and yellow fever vaccination in 3 countries. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Scenario                  | Measles, DynaMICE | Measles, IDM | Measles, Penn State | Men A, Cambridge | Men A, KP Yellow fever, Imperial | Yellow fever, Notre Dame |
|---------------------------|--------------------|-------------|--------------------|------------------|-------------------------------|---------------------------|
| 50% RI                    | 19.1957            | 11.9708     | 6.4030             | 15.9806          | 5.8875                        | 2.5026                    | 1.9177                   |
| Postpone 2020 SIAs -> 2021 | 15.6442            | 1.2587      | -1.3240            | 34.3826          | -4.8384                       | -0.9923                   | -0.2610                  |
| 50% RI, postpone 2020 SIAs -> 2021 | 3.9844            | 13.2423     | 2.8315             | 52.0581          | 0.1766                        | 1.4868                    | 1.3626                   |
### Table S13: Percentage differences in deaths from baseline between 2020-2030 per scenario.

Scenarios for disruption of routine immunisation and delay of mass vaccination campaigns due to the COVID-19 pandemic for measles vaccination in 6 countries, meningococcal A vaccination in 4 countries, and yellow fever vaccination in 3 countries. The counterfactual comparative scenario (BAU – business as usual) is no disruption to routine and campaign immunisation.

| Scenario                                      | Percentage difference from baseline |
|-----------------------------------------------|------------------------------------|
| 50% RI                                        | 9.885481                           |
| Postpone 2020 SIAs -> 2021                   | 3.780423                           |
| 50% RI, postpone 2020 SIAs -> 2021           | 4.802334                           |
Table S14. Coverage assumptions for the counterfactual comparative scenario, determined through consultation with disease and immunisation programme experts across partners at the global, regional, and national levels.

| Assumption                      | Measles                      | Yellow fever                  | Meningococcal A (For countries that have introduced routine) |
|---------------------------------|------------------------------|-------------------------------|-------------------------------------------------------------|
| Routine coverage 2020-2030      | MCV1: Mean of 2015-2019 coverage | YF: Mean of 2015-2019 coverage | MenA: Highest coverage in 2015-2019. If no coverage available (for 1+ full years), use MCV1 mean coverage for 2015-19. Exception: where Men A intro age is ≥15m, use MCV2 highest coverage in 2015-19 |
|                                 | MCV2: Highest coverage in 2015-2019 If no MCV2 coverage in 2015-19, assume 50% of MCV1 mean coverage for 2015-19 | If no YF coverage in 2015-19, use MCV1 mean coverage for 2015-19 | |
| Vaccine introductions           | Assume all countries introduce MCV2 in 2022 if they have not already | Assume all countries introduce YF in 2022 if they have not already | N/A |
| Campaign frequency              | Use historic frequency: interval between last two prospectively planned national SIAs | 2019 and 2020 completed and planned campaigns (both planned and reactive) 2021-2030: Mass preventive campaigns as recommended by the WHO EYE strategy (2016), with updated sequencing; no reactive campaigns | 2019 and 2020 completed and planned campaigns 2021-2030: Assume no campaigns |
| Campaign coverage               | Use coverage of last national SIA | Assume 85% coverage of the subnational target population for all future campaigns in 2020-2030 (and for 2019 campaigns if actual coverage unavailable). | 2019 and 2020 actual/forecast campaign coverage level |
| Term                          | Description                                                                 |
|-------------------------------|-----------------------------------------------------------------------------|
| Country                       | BFA: Burkina Faso  
BGD: Bangladesh  
COD: Democratic Republic of the Congo (DRC)  
ETH: Ethiopia  
GHA: Ghana  
KEN: Kenya  
NER: Niger  
NGA: Nigeria  
SSD: South Sudan  
TCD: Chad |
| Vaccine                       | MCV1: 1st dose measles vaccine, MCV2: 2nd dose measles vaccine, YF: yellow fever vaccine, MenA: meningococcal A vaccine |
| Year                          | Year of vaccination                                                         |
| Age from                      | Minimum age (in years) of the target population                             |
| Age to                        | Maximum age (in years) of the target population                             |
| Age range verbatim            | Age of the target population, as provided by WHO or other coverage source   |
| Coverage (national level)     | Percentage of the target population vaccinated, specified at a national level. |
| Target (national level)       | Number of people in the target age range, in the entire country.            |
| Subnational campaign         | Campaigns which took place sub-nationally, rather than across the whole country. |
| Number vaccinated             | Number of individuals vaccinated in a campaign. Where necessary, a demographic cap was applied to constrain the number vaccinated to be no higher than UNWPP records of the total number in the target age group. (UNWPP: United Nations World Population Prospects, 2019 Revision). |
| Affected by COVID-19          | Values are shown for 2020 campaigns only. FALSE: 2020 campaigns unaffected by COVID-19, e.g. campaigns which took place in early 2020. These campaigns are retained in all disruption scenarios. |
Table S16. Routine coverage values used for the counterfactual comparative (business-as-usual) scenario, following the assumptions in Table S14. Target population taken from United Nations World Population Prospects (UNWPP) 2019 revision.

| Country | Vaccine | Year  | Age from | Age to | Coverage (national level) |
|---------|---------|-------|----------|--------|---------------------------|
| BFA     | MenA    | 2020-2030 | 0        | 0      | 85%                       |
| BGD     | MCV1    | 2020-2030 | 0        | 0      | 97%                       |
|         | MCV2    | 2020-2030 | 2        | 2      | 93%                       |
| COD     | YF      | 2020-2030 | 0        | 0      | 74%                       |
| ETH     | MCV1    | 2020-2030 | 0        | 0      | 64%                       |
|         | MCV2    | 2020-2030 | 2        | 2      | 31%                       |
| GHA     | YF      | 2020-2030 | 0        | 0      | 89%                       |
| KEN     | MCV1    | 2020-2030 | 0        | 0      | 92%                       |
|         | MCV2    | 2020-2030 | 2        | 2      | 45%                       |
| NER     | MenA    | 2020-2030 | 0        | 0      | 96%                       |
| NGA     | MCV1    | 2020-2030 | 0        | 0      | 61%                       |
|         | MCV2    | 2020-2030 | 2        | 2      | 19%                       |
|         | MenA    | 2020-2030 | 0        | 0      | 61%                       |
|         | YF      | 2020-2030 | 0        | 0      | 60%                       |
| SSD     | MCV1    | 2020-2030 | 0        | 0      | 51%                       |
| TCD     | MCV1    | 2020-2030 | 0        | 0      | 39%                       |
| TCD     | MenA    | 2020-2030 | 0        | 0      | 70%                       |
Table S17. Campaign coverage values used for the counterfactual comparative (business-as-usual) scenario, following the assumptions in Table S14.

| Country | Vaccine | Year | Age_from | Age_to | Age_range | Cover_from | Cover_to | Target_national_level | Subnational_campaign | Number_vaccinated | Affected_by_covid-19 |
|---------|---------|------|----------|--------|-----------|------------|----------|-----------------------|---------------------|-------------------|---------------------|
| BGD     | Measles | 2020 | 1        | 9      | 6M-9Y     | 1%         | 26,123,496| yes                   | 292,437             | FALSE             |
| BGD     | Measles | 2020 | 1        | 9      | 9M-9Y     | 100%       | 26,123,496| no                    | 26,123,496         |                   |
| BGD     | Measles | 2026 | 1        | 4      |           | 93%        | 10,972,070| no                    | 10,204,025         |                   |
| COD     | YF      | 2020 | 1        | 60     | 9M-60Y    | 10%        | 82,362,957| yes                   | 8,468,874           |                   |
| COD     | YF      | 2020 | 1        | 60     | 9M-60Y    | 8%         | 82,362,957| yes                   | 6,707,043           |                   |
| COD     | YF      | 2021 | 1        | 60     | 9M-60Y    | 25%        | 84,982,979| yes                   | 21,179,612          |                   |
| COD     | YF      | 2022 | 1        | 60     | 9M-60Y    | 17%        | 87,641,611| yes                   | 14,875,225          |                   |
| COD     | YF      | 2023 | 1        | 60     | 9M-60Y    | 14%        | 90,340,189| yes                   | 12,357,393          |                   |
| COD     | YF      | 2024 | 1        | 60     | 9M-60Y    | 18%        | 93,082,143| yes                   | 17,200,562          |                   |
| ETH     | Measles | 2019 | 1        | 14     | 6M-59M;   | 3%         | 41,766,446| yes                   | 1,230,934           |                   |
| ETH     | Measles | 2020 | 1        | 4      | 6-59 M    | 100%       | 13,314,425| no                    | 13,314,425          |                   |
| ETH     | Measles | 2027 | 1        | 4      |           | 93%        | 14,462,250| no                    | 13,449,892          |                   |
| GHA     | YF      | 2020 | 10       | 60     | 10-60Y    | 22%        | 21,527,602| yes                   | 4,758,966           |                   |
| KEN     | Measles | 2020 | 1        | 4      | 9-59 M    | 100%       | 5,625,900 | no                    | 5,625,900           |                   |
| KEN     | Measles | 2024 | 1        | 4      |           | 95%        | 5,839,639 | no                    | 5,547,657           |                   |
| Location | Disease   | Year | Week | Age | Completion Rate | No. Vaccinated | Comment |
|----------|-----------|------|------|-----|----------------|----------------|---------|
| KEN      | Measles   | 2028 | 1    | 4   | 95%            | 6,220,262      | no      |
| NGA      | Measles   | 2019 | 1    | 9   | 6M-9Y          | 55,695,418     | yes     |
| NGA      | Measles   | 2019 | 1    | 5   | 6M-71M         | 32,616,304     | yes     |
| NGA      | Measles   | 2019 | 1    | 4   | 9-59 M         | 26,413,460     | yes     |
| NGA      | MenA      | 2019 | 1    | 7   | 55%            | 44,499,793     | yes     |
| NGA      | YF        | 2019 | 1    | 44  | 9M-44Y         | 167,255,829    | yes     |
| NGA      | YF        | 2019 | 1    | 44  | 9M-44Y         | 167,255,829    | yes     |
| NGA      | YF        | 2019 | 1    | 44  | 9M-44Y         | 167,255,829    | yes     |
| NGA      | Measles   | 2020 | 1    | 4   | 6-59 M         | 26,844,855     | yes     |
| NGA      | MenA      | 2020 | 7    | 10  | 7-8 / 9-10 yrs | 22,936,865     | yes     |
| NGA      | MenA      | 2020 | 1    | 7   | 1-7 Y          | 45,289,678     | yes     |
| NGA      | YF        | 2020 | 1    | 44  | 9M-44Y         | 171,465,804    | yes     |
| NGA      | YF        | 2020 | 1    | 44  | 9M-44Y         | 171,465,804    | yes     |
| NGA      | YF        | 2020 | 1    | 44  | 9M-44Y         | 171,465,804    | yes     |
| NGA      | Measles   | 2021 | 1    | 44  | 9M-44Y         | 175,731,488    | yes     |
| NGA      | Measles   | 2022 | 1    | 4   | 88%            | 27,691,758     | no      |

Note: The data shows the number of vaccinations and completion rates for various diseases in different locations over different years.
| Country | Disease | Year | Age Group | Reduction | Cases | Success | Date | Value |
|---------|---------|------|-----------|-----------|-------|---------|------|-------|
| NGA     | Measles | 2022 | 1-44      | 13%       | 180,026,007 | yes    | 23,699,548 |
| NGA     | Measles | 2023 | 1-44      | 13%       | 184,355,854 | yes    | 23,699,548 |
| NGA     | Measles | 2024 | 1-4       | 88%       | 28,580,680  | no     | 25,008,095  |
| NGA     | Measles | 2026 | 1-4       | 88%       | 29,575,232  | no     | 25,878,328  |
| NGA     | Measles | 2028 | 1-4       | 88%       | 30,532,880  | no     | 26,716,270  |
| NGA     | Measles | 2030 | 1-4       | 88%       | 31,488,385  | no     | 27,552,337  |
| SSD     | Measles | 2020 | 1-4       | 6-59 M    | 1,350,759   | no     | 1,350,759   | FALSE |
| SSD     | Measles | 2020 | 1-4       | 6-59 M    | 1,350,759   | no     | 659,330     |
| SSD     | Measles | 2023 | 1-4       | 92%       | 1,396,213   | no     | 1,284,516   |
| SSD     | Measles | 2026 | 1-4       | 92%       | 1,465,629   | no     | 1,348,379   |
| SSD     | Measles | 2029 | 1-4       | 92%       | 1,513,497   | no     | 1,392,417   |
| TCD     | Measles | 2019 | 1-9       | 6M-9Y     | 4,729,086   | yes    | 653,511     |
| TCD     | Measles | 2019 | 1-9       | 6M-9Y     | 4,729,086   | yes    | 210,185     |
| TCD     | Measles | 2019 | 1-9       | 6M-9Y     | 4,729,086   | yes    | 298,738     |
| TCD     | Measles | 2019 | 1-9       | 6M-9Y     | 2,259,841   | yes    | 467,456     |
| TCD     | Measles | 2020 | 1-4       | 6M-9M     | 2,306,276   | yes    | 340,046     | FALSE |
| TCD     | Measles | 2020 | 1-4       | 6M-9M     | 2,306,276   | yes    | 43,233      | FALSE |
| TCD     | Measles | 2020 | 1-4       | 6M-9M     | 2,306,276   | yes    | 712,746     |
| TCD     | Measles | 2020 | 1-4       | 9-59 M    | 2,306,276   | no     | 2,306,276   |
| TCD   | Disease | Year | Age | Coverage | Population | Vaccinated | Cases |
|-------|---------|------|-----|----------|------------|------------|-------|
| MenA  | 2020    | 1    | 8-1Y| 15%      | 4,352,395  | yes        | 647,065|
| Measles| 2028    | 1    | 4  | 82%      | 2,681,750  | no         | 2,199,035|
Figures (appendix)

Figure S1: Health impact of predicted total disability-adjusted life years for immunisation disruption scenarios and no disruption scenario for measles, meningococcal A, and yellow fever.

The average model predicted total disability-adjusted life years (DALYs) per 100,000 population per year for routine and campaign immunisation disruption scenarios and no disruption scenario (BAU – business-as-usual scenario) for measles, meningococcal A, and yellow fever during 2020-2030. The grey ribbon indicates the most extreme model estimates for all scenarios, that is for infections with two models – these lines indicate maximum and minimum model projections for all scenarios; the thick line indicates mean model projection.
Figure S2: Health impact of excess disability-adjusted life years for immunisation disruption scenarios in comparison to no disruption scenario for measles, meningococcal A, and yellow fever.

The average model predicted excess disability-adjusted life years (DALYs) per 100,000 population per year for routine and campaign immunisation disruption scenarios in comparison to no disruption scenario (BAU – business-as-usual scenario) for measles, meningococcal A, and yellow fever. Excess DALYs are summed over 2020-2030, and the error bars indicate the range in model projections.
Figure S3: Health impact of normalised excess deaths for immunisation disruption scenarios in comparison to no disruption scenario for measles, meningococcal A, and yellow fever. The normalised average model predicted excess deaths per year for routine and campaign immunisation disruption scenarios in comparison to no disruption scenario (BAU – business-as-usual scenario) for measles, meningococcal A, and yellow fever. Excess deaths are summed over 2020-2030, and the excess deaths are normalised by setting the BAU to 0 and maximum to 1.
Figure S4: Health impact of normalised excess disability-adjusted life years for immunisation disruption scenarios in comparison to no disruption scenario for measles, meningococcal A, and yellow fever. The normalised average model predicted excess disability-adjusted life years (DALYs) per year for routine and campaign immunisation disruption scenarios in comparison to no disruption scenario (BAU – business-as-usual scenario) for measles, meningococcal A, and yellow fever. Excess DALYs are summed over 2020-2030, and the excess DALYs are normalised by setting the BAU to 0 and maximum to 1.
Figure S5: Health impact of predicted total deaths for immunisation disruption scenarios and no disruption scenario for measles. Model predicted total deaths per 100,000 population per year for routine and campaign immunisation disruption scenarios and no disruption scenario (BAU – business-as-usual scenario) for measles during 2020-2030 per modelling group.
Figure S6: Health impact of predicted total deaths for immunisation disruption scenarios and no disruption scenario for meningococcal A. Model predicted total deaths per 100,000 population per year for routine and campaign immunisation disruption scenarios and no disruption scenario (BAU – business-as-usual scenario) for meningococcal A during 2020-2030 per modelling group.
Figure S7: Health impact of predicted total deaths for immunisation disruption scenarios and no disruption scenario for yellow fever. Model predicted total deaths per 100,000 population per year for routine and campaign immunisation disruption scenarios and no disruption scenario (BAU – business-as-usual scenario) for yellow fever during 2020-2030 per modelling group.
Model descriptions (appendix)

Measles Model - PSU

The Penn State model is a measles transmission and vaccination model developed at Pennsylvania State University. It is an age-structured compartmental transmission dynamic model with compartments for susceptible, infected, recovered (due to infection or vaccination) subpopulations. A proportion of infected people will die depending on their age and country characteristics, as per the LSHTM model. The model projects the total number of infections and deaths in 1-year age cohorts, up to age 100 years, in each year according to an annual attack rate that is modeled as a logistic function of the annualized proportion of the population that is susceptible. The slope and intercept of this logistic function, which governs the proportion of available susceptibles that are infected in each year, is fitted independently for each country to observed annual case reporting and vaccination coverage (routine and supplemental campaigns) for each country between 1980-2017; for details on the fitting methods see Eilertson et al. Historical annual surveillance data is not available for all countries and thus these parameters cannot be estimated; specifically, for Palestine and Kosovo we use the average of parameter values for all other countries, for South Sudan, we use the parameter estimates for Sudan. Vaccine efficacy for routine immunization is assumed to depend on the age at first dose (9m or 12m) as described in Simons et al. The second routine dose is assumed to be preferentially delivered to those children who received the first dose and SIA doses are assumed to be independent of receipt of the first routine dose.

Measles Model - DynaMICE

DynaMICE (DYNAmic Measles Immunisation Calculation Engine) is a measles transmission and vaccination model developed by LSHTM with input from Harvard University and the University of Montreal. It is an age-structured compartmental transmission dynamic model with compartments for maternal immune, susceptible, infected, recovered, and vaccinated subpopulations. A proportion of infected people will die depending on their age and country characteristics. The population is also stratified by age with weekly age classes up to age 3 years, and annual age classes thereafter up to 100 years. The force of infection is calculated by combining an age-dependent social contact matrix from the POLYMOD study, demographic distribution for each country, and an estimated probability of transmission per contact. The probability of transmission per contact is then estimated from the basic reproduction number of measles using the principal eigenvalue method. Vaccination is incorporated as a pulse function and can be delivered to any age or range of ages and in either routine or campaign delivery. Vaccine efficacy is dependent on age and the number of doses received. The model has been previously described in detail.

Measles Model - IDM

The IDM model for Nigeria was built using EMOD – an agent-based stochastic disease transmission model. The EMOD software is open-source, and the model and documentation of the EMOD
software are available at the IDM website. The model presented here is a discrete-time (daily time steps), an individual-based form of an MSEIR (maternally protected-susceptible-exposed-infectious-recovered) model. A specific prior application of the EMOD model to measles in Nigeria is described in Zimmermann et al; the model employed here is similar but is structured at a finer spatial scale. The transmission dynamics include seasonality, age-stratified heterogeneous transmission, and spatial metapopulations coupled by migration, the parameters of which have been calibrated to reproduce the seasonality, age-distribution, and spatial correlation of measles cases in Nigeria. Routine vaccination with a first dose is delivered to covered individuals at 9 months of age; the second dose at 12 months; and SIA vaccination is distributed to covered individuals in the target age range in a pulse over the course of 2 weeks; no correlation between the two routine doses or between the routine and SIA doses is assumed.

**Men A Model - Cambridge**

The University of Cambridge MenA model is a compartmental transmission dynamic model of *Neisseria meningitidis* group A (NmA) carriage and disease to investigate the impact of immunisation with a group A meningococcal conjugate vaccine, known as MenAfriVac, as published by Karachaliou et al. The model is age-structured (1-year age groups up to age 100) with continuous ageing between groups. Model parameters were based on the available literature and African data wherever possible, with the model calibrated on an ad-hoc basis as described below.

The population is divided into four states, which represent their status with respect to the meningitis infection. Individuals may be susceptible, carriers, ill or recovered, and in each of these states be vaccinated or unvaccinated, with vaccinated individuals having lower risks of infection (carriage acquisition) and disease (rate of invasion). We assume that both carriers and ill individuals are infectious and can transmit the bacteria to susceptible individuals. The model captures the key features of meningococcal epidemiology, including seasonality, which is implemented by forcing the transmission rate, the extent of which varies stochastically every year.

Since only a small proportion of infected individuals develop the invasive disease, disease-induced deaths are not included in the model. From each compartment, there is a natural death rate from all causes. Carriage prevalence and disease incidence vary with age, and the model parameterised these distributions using a dataset from Niger; the case:carrier ratio consequently varies with age. The duration of 'natural immunity' is an important driver of disease dynamics in the absence of vaccination but good data on this parameter is lacking; instead, prior estimates are used.

The model assumes that mass vaccination campaigns occur as discrete events whereas routine immunisation takes place continuously. We allowed the duration of protection to vary uniformly between 5 years and 20 years for the 0-4-year-olds and 10-20 years for over 5-year-olds. For the 200 runs, we selected pairs of values for these two parameters so that duration of protection for the older age group is not shorter than the duration of protection for 0-4-year-olds. Vaccine efficacy against carriage and disease is 90%.
Disease surveillance is not comprehensive across the meningitis belt, so the disease burden is uncertain in several countries. Therefore, the model classifies the countries into three categories, based on the incidence levels using historical data. This classification defines the transmission dynamic parameters. The model generates estimates of case incidence, to which a 10% case-fatality ratio is applied to estimate mortality. To estimate DALYs it is assumed that 7-2% of survivors have major disabling sequelae with a disability weight of 0.26.

Countries were stratified into high and medium risk, and different infection risks applied based on this stratification. As there was insufficient information to define infection risk on a country-by-country basis, the approach/stratification was agreed upon with experts in the WHO meningitis team. For countries only partly within the meningitis belt, only the (subnational) area at risk was included.

To produce estimates on the impact of vaccination, 200 simulation runs were generated by stochastically varying the baseline transmission rate to reflect between-year climactic or another external variability. Although each individual simulation reflects the reality of irregular and periodic epidemics, as visually compared to time series from Chad and Burkina Faso and analysis of interepidemic periods, the resulting averaged estimates give a stable expected burden of disease over time. Uncertainty in other model parameters is currently not quantified.

**Men A Model - KP**

The KP model for serogroup A Neisseria meningitidis (MenA) was developed at Kaiser Permanente Washington in partnership with the US Centers for Disease Control and Prevention and the Burkina Faso Ministry of Health. It is a dynamic, age-structured, stochastic compartmental transmission model, with compartments to represent MenA colonization, disease, and immunity. Natural infection with MenA is assumed to lead to resistance to future colonization and disease, and repeated infections further reduce risk, although protection wanes over time. The age-dependent force of infection (“who acquires infection from whom”) matrix varies seasonally to account for differential MenA transmission between dry and rainy seasons. Model parameters, including the force of infection, were estimated using approximate Bayesian calculation, with prior distributions informed by the literature. Mass campaigns occur among persons aged 1-29 years (possibly with catch-up campaigns at the initiation of routine immunization), in which immunization is assumed to occur in the first week of the month during which a campaign is scheduled. Routine immunization is assumed to occur during the first week of the month in which a child reaches 9 months of age.

**Yellow Fever Model - Imperial College London**

The Imperial College London yellow fever model is a static transmission model assuming a constant force of infection (FOI) for each country at risk of YF. It is estimated from YF occurrence data as well as serological data where available. The model also uses environmental covariates, information on vaccination activities, and demographic projections to estimate relative risk and thus transmission
intensity for YF. The original framework was developed by Garske et al.\textsuperscript{20} and was subsequently extended by Jean et al\textsuperscript{21} and Gaythorpe et al\textsuperscript{22}. The full model description is given in Gaythorpe et al.\textsuperscript{22}

**Yellow Fever Model - University of Notre Dame**

The University of Notre Dame yellow fever (YFV) model is a static transmission model that assumes a constant force of infection (FOI) for each endemic country.\textsuperscript{23} Yellow fever infections in the human population are thus modeled as spillover events from non-human primates, so human-to-human transmission observed in urban outbreaks is not considered. Accordingly, our model is intended to capture long-term changes in YFV burden on account of changes in vaccination coverage rather than to realistically capture interannual variability due to YFV epizootics in non-human primates and occasional outbreaks in humans.

We calibrated our YFV transmission model to multiple sources of epidemiological data collected in sub-Saharan Africa at the first administrative level subnationally. First, we quantified past exposure to YFV by estimating the force of infection in 23 administrative units using data collected in serological surveys. We then related the predicted number of YFV infections at each of the 23 administrative units to the corresponding reported outbreak data collated by Garske et al\textsuperscript{20} to quantify the extent of underreporting. We then obtained estimates of the total number of infections at each administrative unit in sub-Saharan Africa by relating our estimates of underreporting to the total number of reported cases and deaths in each administrative unit. This allowed us to estimate a posterior distribution of a single FOI for each administrative unit in sub-Saharan Africa. Because the FOIs that we estimated are sensitive to the number of reported cases and deaths, we smoothed across our estimates by performing a regression analysis with spatial covariates. We considered multiple regression models and generated an ensemble prediction by weighting the predicted FOI from each regression model based on performance in ten-fold cross-validation at the country level. National-level FOI estimates were obtained by weighting the ensemble spatial prediction of FOI according to WorldPop 2015 population density estimates at the first administrative level and then summing to obtain national FOIs.\textsuperscript{24}

To project the number of yellow fever cases and deaths in each country under a given vaccination coverage scenario, we first scaled the national-level FOI by the proportion of the population that is unvaccinated. We then used the scaled FOI estimate to project the annual number of YFV infections and multiplied this quantity by the probabilities of disease and death reported by Johansson et al\textsuperscript{25} to obtain estimates of the annual number of YFV cases and deaths. We assume a 0.975 probability of protection from infection among those who are vaccinated based on Jean et al,\textsuperscript{26} with this level of protection assumed to be lifelong based on a single dose. In the event of campaigns, we assume that individuals are vaccinated randomly and irrespective of prior vaccination through another campaign or routine vaccination.
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Orderly id: 20210111-162259-37bada66

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