FROM ENDGAME TO LONG GAME:

A MULTI-METHOD ANALYSIS OF

IMMUNIZATION, INTEGRATION, AND EQUITY DURING

OUTBREAK RESPONSE AND RECOVERY IN

LOW- AND MIDDLE-INCOME COUNTRIES

by
Sanjana Jayalakshmi Ravi

A dissertation submitted to Johns Hopkins University
in conformity with the requirements for the degree of Doctor of Philosophy

Baltimore, Maryland
April 2022

ABSTRACT

Background: Achieving and sustaining high levels of equitable immunization coverage during and after outbreaks remains a major public health challenge for many health systems in low- and middle-income countries (LMICs).

Objectives: The objectives of this dissertation are to (1) describe vaccine delivery challenges that emerge during the last mile of outbreak response; (2) explore how routine immunization programs recover from epidemics; and (3) characterize the relationship between integrated vaccine delivery and equitable vaccination coverage. The ultimate goal of this investigation is to inform how decision-makers in LMICs might strengthen or reform vaccination systems to increase equitable immunization coverage.

Methods: Paper 1 presents a conceptual framework of last mile challenges in vaccine delivery during outbreaks, based on a scoping literature review and key informant interviews. Paper 2 presents a comparative case study analysis of post-epidemic routine immunization challenges in Haiti and Liberia. Paper 3 applies group-based trajectory modeling to describe longitudinal trends in vaccination equity in 78 LMICs and examine associations between integrated vaccine delivery and equity.

Results: In Paper 1, we find that last mile challenges in vaccine delivery may be conceptualized in terms of geography, epidemiology, target populations, and health system considerations, and span the domains of governance and leadership, surveillance, health workforces, program implementation, vaccine uptake, and population immunity. In Paper 2, we find that embedding in-country expertise within outbreak response structures, respecting governmental autonomy and self-determination, aligning post-epidemic recovery plans and policies, and integrating response assets into systems for routine care resulted in more equitable levels of immunization coverage. In Paper 3, we report positive associations between integrated vaccine delivery and both geographic and socioeconomic vaccination equity in select settings reporting high baseline levels of vaccination inequity.

Conclusions: The health system challenges associated with achieving and sustaining high levels of equitable immunization coverage differ between pre-, post-, and inter-outbreak periods. Strengthening linkages within and between relevant health system components can help address these challenges in LMICs. Further research is needed to characterize the barriers and facilitators of equitable vaccine delivery in these settings.

THESIS ADVISORS & READERS

Thesis Advisor
Maria Merritt, PhD
Department of International Health

Committee Chair
Nancy E. Kass, ScD
Department of Health Policy and Management

Thesis Readers
Christopher D. Heaney, PhD
Department of Environmental Health and Engineering

Bryan N. Patenaude, ScD
Department of International Health

Alternate Readers
Caitlin E. Kennedy, PhD, MPH
Department of International Health

Carl Latkin, PhD
Department of Health, Behavior and Society

Thesis Advisory Committee Members
Jessica E. Atwell, PhD, MPH
Department of International Health

Ligia Paina, PhD
Department of International Health

ACKNOWLEDGEMENTS

First and foremost, I owe an enormous debt of gratitude to Dr. Maria Merritt, my academic advisor, for her incredible mentorship over the past four years. Being Maria's student has been an education in navigating academia with generosity, integrity, empathy, and kindness, and I can only hope to emulate her example in my own career. I'm also grateful to Dr. Abdul Bachani for graciously serving as my interim advisor during my third year, and especially to Cristina Salazar and Audrey Lindahl, whose infinite patience and guidance made navigating the PhD program possible.

I've also benefited tremendously from the support of many dedicated faculty and students at Hopkins. In addition to Maria, Drs. Bryan Patenaude, Ligia Paina, and Jessica Atwell provided invaluable feedback on my work, helping me become a more capable thinker, writer, and researcher. Dr. Andrés Vecino-Ortiz, too, very kindly guided me through the analysis presented in Paper 3. I also thank the members of my preliminary oral exam committees for helping sharpen my vision for this thesis, my Committee of Thesis Readers for reviewing the final product, and especially the members of my writing accountability group for the motivation to cross the finish line.

I'm profoundly grateful to my phenomenal colleagues at the Johns Hopkins Center for Health Security, where I've been lucky to learn from the best of the best. D.A. Henderson was an early source of inspiration and encouragement to earn a PhD, Tom Inglesby and Anita Cicero have been unfailingly generous in allowing me to work part-time while pursuing my degree, and the Center's senior scholars have provided me with a wealth of opportunities to grow professionally over the years. A heartfelt thank you goes to Hannah Ottman-Feeney, who patiently scheduled round after round of interviews for this project, and especially to Christina Potter, who cheerfully helped me review countless papers, enter data, and transcribe interviews over the past two years. Her frequent rallying cry of "we're gonna bust you out of grad school" was also a source of much-needed inspiration during low points. And, of course, I raise a toast to my fellow members of the A-Team: working with you all has been the best part of my career.

I’ve also had the support of extraordinary friends over the past several years: Ankit Agrawal, Nidhi Bouri, Veni Kandasamy, Joanna Williams, Diane Meyer, Lucia Mullen, Marc Trotochaud, Lane Warmbrod, and Sindhu Balasubramanian. Our game nights, phone calls, happy hours, coffee runs, and Zoom lunches provided a much-needed respite from writing a dissertation about vaccines in the middle of a pandemic.

Finally, this thesis has served as a constant reminder of the enormous familial sacrifices underpinning my education. My grandmother, Padmavati, left school as a teenager to care for her family and later spent several years of her retirement raising me. My parents, Surendra and Saroja, immigrated to the U.S. as young adults, both foregoing opportunities to pursue their passions in favor of building a stable family life. My parents and grandmother worked every day, night, and weekend of their lives so that I might have the freedom to determine the course of my own. The life of scholarship and learning that I am so privileged to enjoy now – a life that would have been unimaginable even a generation ago – became possible only through their love and effort. I hope the work captured in these pages honors their sacrifices, if only in a small way. And last, but certainly not least, a million thanks go to my brother, Saagar, for endless laughs, encouragement, and advice: the best reminders of what’s really important in life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

"Here is a thought experiment: imagine a country without a health system; the chaos, the inefficiency. The only form of health systems research one should conduct in a country without a health system is that which generates evidence to drive policy towards creating a system to achieve universal coverage. The research should not only be about which interventions work best, but within which settings the interventions that work best would be optimal."

Ṣẹ̀yẹ Abímbọ́lá

"Health Systems in an Interconnected World: A View from Nigeria"

1.1 Background

Infectious disease outbreaks pose significant threats to population health and well-being. Left unchecked, outbreaks not only cause illness and death at large scales, but also slash the social fabric of affected communities by giving rise to complex governance challenges, eroding trust in public health and health care institutions, and generating long-term psychosocial challenges as a result of prolonged communal morbidity and mortality. Outbreaks also carry severe economic consequences: due to the ongoing COVID-19 pandemic, for example, the International Monetary Fund estimates that the global economy contracted by 3.5% in 2020, the worst recession since the end of World War II.[1] Even common childhood infections like measles prove costly in well-resourced and resource-constrained settings alike: for instance, the societal cost of responding to a 2019 measles outbreak in a single United States county was estimated at USD$3.4 million (USD$47,479 per case).[2] Finally, outbreaks place enormous strains on health systems by diverting limited resources and impeding efforts to provide routine services, perform core public health functions, and ensure equitable care amid increased demands for emergency health services.

Acute outbreaks are not the only context in which infectious diseases imperil well-being and livelihoods. Diseases like HIV/AIDS, malaria, tuberculosis, cholera, and syphilis have ravaged populations for decades, if not centuries, and remain endemic in many parts of the world, especially low- and middle-income countries (LMICs). As the world grapples with the legacies of these diseases and their disparate impacts, wrestles with the challenges wrought by COVID-19 and other emerging infections, and prepares for future epidemics and pandemics, the imperative to develop more cohesive strategies for managing infectious disease threats grows increasingly urgent.

Vaccines are arguably among the most clinically robust and cost-effective tools in public health arsenals for preventing and mitigating infectious disease. In this vein, the United Nations' Sustainable Development Goals call for "safe, effective, quality and affordable essential medicines and vaccines for all," and strongly affirm the importance of achieving universal health coverage.[3,4] Yet, delivering vaccines to the point of care and ensuring sufficient uptake – both during routine immunization and outbreak response – remain critical health system challenges, as does ensuring equitable immunization coverage globally.

The nature of these challenges varies across phases of outbreak prevention, mitigation, response, and recovery. For example, an important subset of vaccination challenges emerges during the so-called "last mile" of outbreak response. In the context of disease elimination and eradication efforts, "the last mile" typically refers to the phase in which public health interventions have successfully reduced burdens of a given disease to a point where only a few cases remain. Scholars often describe the last mile of a public health intervention targeting communicable diseases as "the longest mile," citing escalating costs, losses of political momentum, the risk of emergent drug resistance, and evolution of greater virulence as key challenges distinct from those encountered in earlier phases of preparedness and intervention.[5–8]

In addition to the complexity of vaccine delivery during outbreaks, the post-epidemic recovery challenges faced by routine immunization programs are similarly daunting. Lessons learned from past public health emergencies suggest that health systems should ideally possess the ability to scale up robust baseline capacities for routine service provision to meet the demands of emergent crises, including outbreaks. However, this logic fails in resource-constrained settings, where baseline capacities may be weak or altogether missing. As a result, routine immunization programs often suffer disruptions during and after outbreaks in the form of staffing shortages, diverted funds and resources, and increased risks associated with patient-provider contact.[9–11] In fact, the World Health Organization (WHO) reported in 2020 that at least 24 million people in countries receiving support from Gavi, the Vaccine Alliance were at risk of missing vaccinations against polio, measles, yellow fever, rotavirus, and other diseases due to postponed campaigns and vaccine introductions attributed to the COVID-19 pandemic.[12] Thus, decision-makers in settings recovering from outbreaks must identify strategies for transitioning resources for emergency vaccination efforts into post-epidemic activities to build or strengthen capacities for routine immunization.

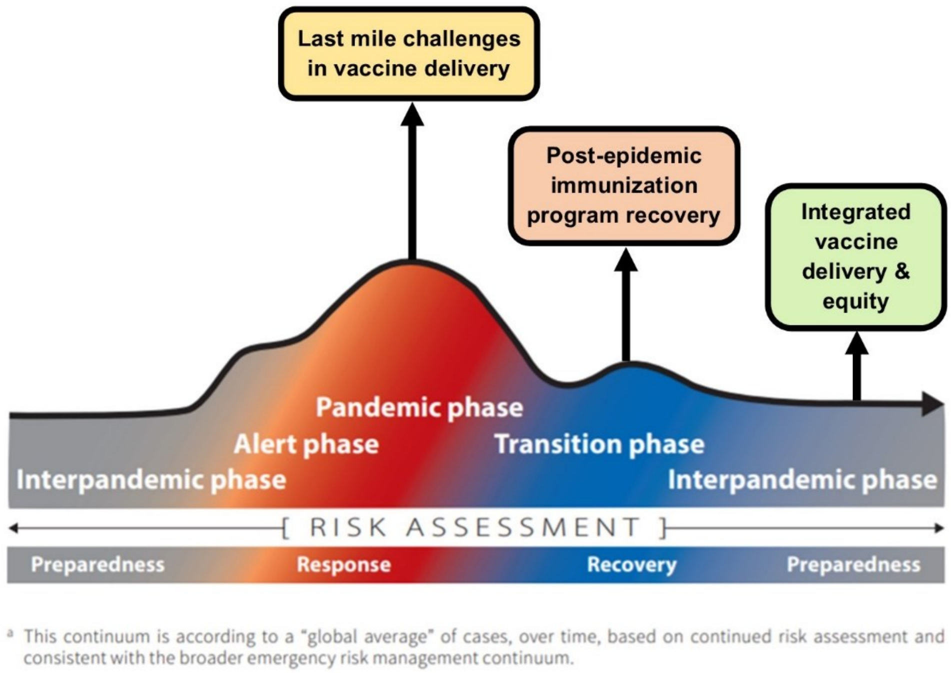
Vaccination challenges also persist during interpandemic periods. In this context, the vaccination considerations and health system demands associated with outbreak response and post-epidemic recovery mirror a longstanding tension between vertical and horizontal approaches to health service delivery. Generally, immunization services may be delivered horizontally, via publicly financed systems designed to provide comprehensive health care, or vertically, via disease-specific, often freestanding programs that may not be fully integrated into the broader health system.[13,14] Vertical interventions are a hallmark of vaccine delivery during outbreaks (e.g., mass vaccination campaigns), whereby external resources are typically channeled into disease-specific response efforts. However, vertical efforts are often costly and resource-intensive – and, in settings with fragile health systems and deeply entrenched inequities in health service access, demonstrate limited effectiveness in terms of sustaining equitable immunization coverage.[14–16] Though public health responders generally rely on vertical modes of vaccination during outbreaks, a considerable body of evidence affirms the value of horizontal (i.e., "integrated") mechanisms for routine immunization, whereby vaccination is linked to other essential health services (e.g., vitamin A supplementation, deworming, bednet distribution) within a comprehensive primary care system.[17–19] Furthermore, there is some evidence that integrated vaccine delivery can help reduce vaccination inequities in LMICs.[20,21]

Given the public health importance of equitable vaccine delivery and uptake both during and after infectious disease outbreaks, this thesis aims to describe vaccine delivery challenges that emerge during the last mile of outbreak response, explore how routine immunization programs recover from epidemics, and characterize the relationship between integrated vaccine delivery and equitable vaccine coverage. The ultimate goal of this investigation is to inform how public health practitioners, researchers, and decision-makers in LMICs might strengthen or reform vaccination systems to increase equitable immunization coverage.

1.2 Conceptual Framework and Research Paradigm

This thesis contextualizes the aforementioned vaccination challenges in terms of WHO's continuum of pandemic phases, which illustrates how case numbers ebb and flow through various stages of an outbreak.[22] In Figure 1 on the following page, we modify WHO's continuum slightly to illustrate how the foci of this investigation described previously – last mile challenges in vaccine delivery, post-epidemic routine immunization recovery, and integrated vaccine delivery and vaccination equity – correspond to select phases.

Figure 1. Modified Conceptual Model of Pandemic Phases and Investigation Foci



Broadly, our investigation adopts a pragmatist research paradigm, which underpins much of health systems and health services research. Given the inherent complexity of conducting such research, Long et al. endorse pragmatism as a suitable epistemic foundation for inquiry in these areas.[23] The pragmatist paradigm posits that both quantitative and qualitative methods comprise valid approaches to answering health systems research questions, and that the research question under pursuit should determine the method of inquiry to be applied.[24,25] Furthermore, several features of the pragmatic research paradigm align with health systems research considerations, including the importance of contextualizing knowledge and continual learning, positioning research as a force for social action and progress, and valuing different forms of knowledge and knowledge-gathering.[23] In a similar vein, Ogilvie et al. advocate for “pragmatic pluralism” in global health research, whereby scholars “[construct] ‘dry stone walls’* of evidence, robust enough to support more plausible causal inference to guide action, while accepting and adapting to the reality of the public health landscape rather than wishing it were otherwise.”[26]

1.3 Overview of Research Questions, Aims, and Methods

Building on the conceptual framework in Figure 1, this thesis applies a multi-method approach to investigating three critical health system considerations for vaccination in LMIC contexts: 1) last mile challenges in vaccine delivery and uptake during outbreaks; 2) post-epidemic routine immunization program recovery; and 3) the relationship between integrated vaccine delivery and vaccination equity. Below, we present the specific research questions motivating this investigation, along with high-level summaries of their associated aims and methods.

Research Question 1: What challenges emerge during the last mile of vaccine delivery and uptake during outbreaks in LMICs?

Aim 1: Construct a conceptual framework illustrating last mile challenges in vaccine delivery and uptake during outbreaks in LMICs.

---

* Ogilvie et al. propose “dry stone walling” – a process whereby individual stones are assembled into a standing wall, sans mortar – as a metaphor for transforming disparate bodies of evidence into new and useful forms of knowledge.

In Paper 1, we report findings from a scoping literature review and key informant interviews to characterize last mile challenges in vaccine delivery and uptake during outbreaks in LMIC settings, and then organize salient challenges in a conceptual framework featuring four framings of the last mile. These framings include the geographic last mile, which encompasses vaccine delivery challenges relating to remote or rugged terrain, long distances between households and health facilities, absence of transportation, seasonal trends, and poor climate adaptation; the epidemiological last mile, which refers to challenges that emerge during the final stages of disease elimination or eradication efforts; the target population last mile, which features vaccine delivery challenges compounded by socioeconomic disadvantage; and the health system last mile, challenges relating to health system performance and public demand for vaccines impede delivery and uptake. We conclude with implications for public health preparedness policy and recommendations for strengthening outbreak response capacities in LMICs.

Research Question 2: How do health systems recovering from major epidemics strengthen capacities for routine immunization?

Aim 2: Identify barriers and facilitators of post-epidemic routine immunization program recovery in LMICs.

In Paper 2, we share findings from a comparative case study analysis to understand how routine immunization programs in LMICs recover from catastrophic epidemics. Drawing from key informant interviews, the peer-reviewed and grey literature, and quantitative databases, we examine the trajectories of routine immunization programs in the Republics of Liberia and Haiti following the 2014-16 West Africa Ebola epidemic and the 2010s cholera epidemic, respectively. Finally, we use the Essential Public Health Services Framework to perform a cross-case comparison of barriers and facilitators of equitable immunization coverage in both settings and discuss lessons learned from each case.

Research Question 3: Is there a relationship between integrated vaccine delivery and vaccination equity?

Aim 3: Examine the relationship between integrated vaccine delivery and vaccination equity in LMICs.

In the third and final paper of this thesis, we consider the relationship between integrated vaccine delivery, geographic vaccination equity, and socioeconomic vaccination equity in LMICs that have ever received support from Gavi, the Vaccine Alliance. Using publicly available secondary data, we construct a series of group-based trajectory models to examine longitudinal trends in vaccination equity in these countries, explore whether integration is associated with more equitable measles immunization coverage, and identify predictors of country membership in high- and low-performing groups. Finally, we reflect on challenges associated with measuring equity and integration and suggest directions for future analyses.

AIM ONE

Last Mile Challenges in Vaccine Delivery and Uptake

During Outbreaks in Low- and Middle-Income Countries

"Of a sudden Castel's anti-plague injections scored frequent successes, denied it until now. Indeed all the treatments the doctors had tentatively employed, without definite results, now seemed almost universally efficacious. It was as if the plague had been hounded down and cornered, and its sudden weakness lent new strength to the blunted weapons so far used against it."

Albert Camus

The Plague

2.1 ABSTRACT

Vaccines are among the most powerful tools in public health arsenals for combating infectious disease outbreaks. Yet, delivering vaccines to the point of care, promoting uptake, and increasing immunization coverage remains an urgent public health challenge, particularly in low- and middle-income countries (LMICs). The so-called "last mile" of vaccine delivery is the final phase of vaccine delivery required to achieve whatever public health goal the vaccine delivery program is intended to serve, whether to control, eliminate, or eradicate a vaccine-preventable disease. The last mile poses operational challenges that are distinct from those associated both with routine immunization activities and with earlier phases of outbreak response. We conducted a

scoping literature review and key informant interviews and used our findings to construct a conceptual framework of last mile challenges in vaccine delivery during outbreaks in LMICs. We offer the conceptual framework as a resource for public health practitioners and policymakers in LMICs in support of systematic consideration of last mile challenges in vaccine delivery during outbreaks. The framework may also be relevant to broader epidemic planning and long-term health systems-strengthening efforts.

2.2 BACKGROUND

Infectious disease outbreaks pose major threats to health systems across the world, requiring public health practitioners, healthcare professionals, and decision-makers (e.g., those in governments, ministries of health, and international organizations) to invest considerable resources in strengthening capacities for outbreak preparedness and response. Vaccines are among the most cost-efficient and clinically effective tools in public health arsenals for preventing and mitigating outbreaks. Yet, delivering vaccines to the point of care remains a critical health system challenge across high-, middle-, and low-income settings – one that typically evolves over the course of an outbreak. The so-called "last mile" of vaccine delivery is the final phase of vaccine delivery required to achieve whatever public health goal the vaccine delivery program is intended to serve, whether to control, eliminate, or eradicate a vaccine-preventable disease.[27] The last mile poses operational challenges that are distinct from those associated both with routine immunization activities and with earlier phases of outbreak response, particularly in low- and middle-income countries (LMICs). Explicitly characterizing last mile challenges in vaccine delivery and uptake during outbreaks in LMICs could help inform preparedness and planning efforts in these settings, lend greater clarity to capacity-building for outbreak response, and generate important operating principles for public health practice.

"The last mile," a term with origins in the telecommunications industry, refers to the final segment of network(s) that deliver telecommunications services to consumers.[28] It has since been adopted widely across many fields – transportation, supply chain management, humanitarian response, and others – to colloquially describe any final leg, metaphorical or literal, of efforts to distribute goods or services to their intended destination.[29,30] Historically, last mile challenges in public health have been articulated almost exclusively in terms of logistical or distributional challenges, such as transporting vaccines to remote populations without compromising cold chains, eliminating supply chain bottlenecks for essential medicines, or delivering relief in post-disaster settings.[31,32] However, other last mile barriers merit similar consideration.

The absence of widely embraced definitions for "epidemics" and "pandemics" complicates efforts to articulate the boundary conditions of the last mile, though the World Health Organization (WHO) does offer a working definition for "outbreaks": the occurrence of more cases of disease than expected in a given area among a specific group of people over a particular period of time.[27,33,34] Defining an appropriate endpoint to outbreak response efforts presents another important challenge in conceptualizing last mile vaccine delivery and uptake, due largely to the differing health system considerations associated with disease control, elimination, and eradication.[27] In many cases, the desired endpoint of outbreak response and the decision to control, eliminate, or eradicate a disease are both socially and politically determined. Describing the possibility of SARS-CoV-2 endemicity in the United States, for example, the science journalists Jacob Stern and Katherine J. Wu write, “Endemicity, then, just identifies a pathogen that’s fixed itself in our population so stubbornly that we cease to be seriously perturbed by it. We tolerate it. Even catastrophically prevalent and deadly diseases can be endemic, as long as the crisis they cause feels constant and acceptable to whoever’s thinking to ask.”[35]

The diversity of vaccine delivery and uptake challenges further preempts a concise definition of the last mile. Despite availability of an effective vaccine and a robust health system, for instance, the United Kingdom lost its measles elimination status in 2019 due to nearly 1,000 reported cases across England and Wales; UK health officials cited vaccine hesitancy and misinformation as key factors contributing to low uptake.[36] Similarly, recurrent challenges associated with seasonal influenza further suggest that distributional and logistical hurdles are not solely responsible for low immunization coverage: community perceptions of risk associated with flu, public health messaging, and pre-existing conditions (e.g., chronic health issues, pregnancy) also function as powerful modulators of vaccine uptake.[37,38] In the case of polio eradication, political instability, community resistance, and limited vaccine coverage among hard-to-reach populations have contributed to the disease’s persistence despite investments of nearly USD$20 billion via the Global Polio Eradication Initiative (GPEI) since its inception in 1988.[39] Finally, the ongoing COVID-19 pandemic has highlighted the ethical complexities of ensuring equitable vaccine allocation in last mile contexts, as socioeconomically disadvantaged populations in many countries report lower levels of vaccine confidence, access, and uptake compared to their better-off counterparts.[40–42]

These examples underscore a need for targeted analyses of last mile challenges in vaccine delivery and uptake during outbreaks, particularly in LMICs. The last mile is often described as the “longest” or “hardest” mile due to the unique financial, behavioral, ethical, technical, sociopolitical, logistical, and even biological challenges that it may pose to vaccine delivery efforts during outbreaks in LMICs.[43] Regardless of whether the end goal of the outbreak response effort in question entails disease control, elimination, or eradication, an evidence-based typology of relevant challenges could inform how public health practitioners and policymakers in LMICs plan for outbreaks and undertake longer-term health systems-strengthening efforts.

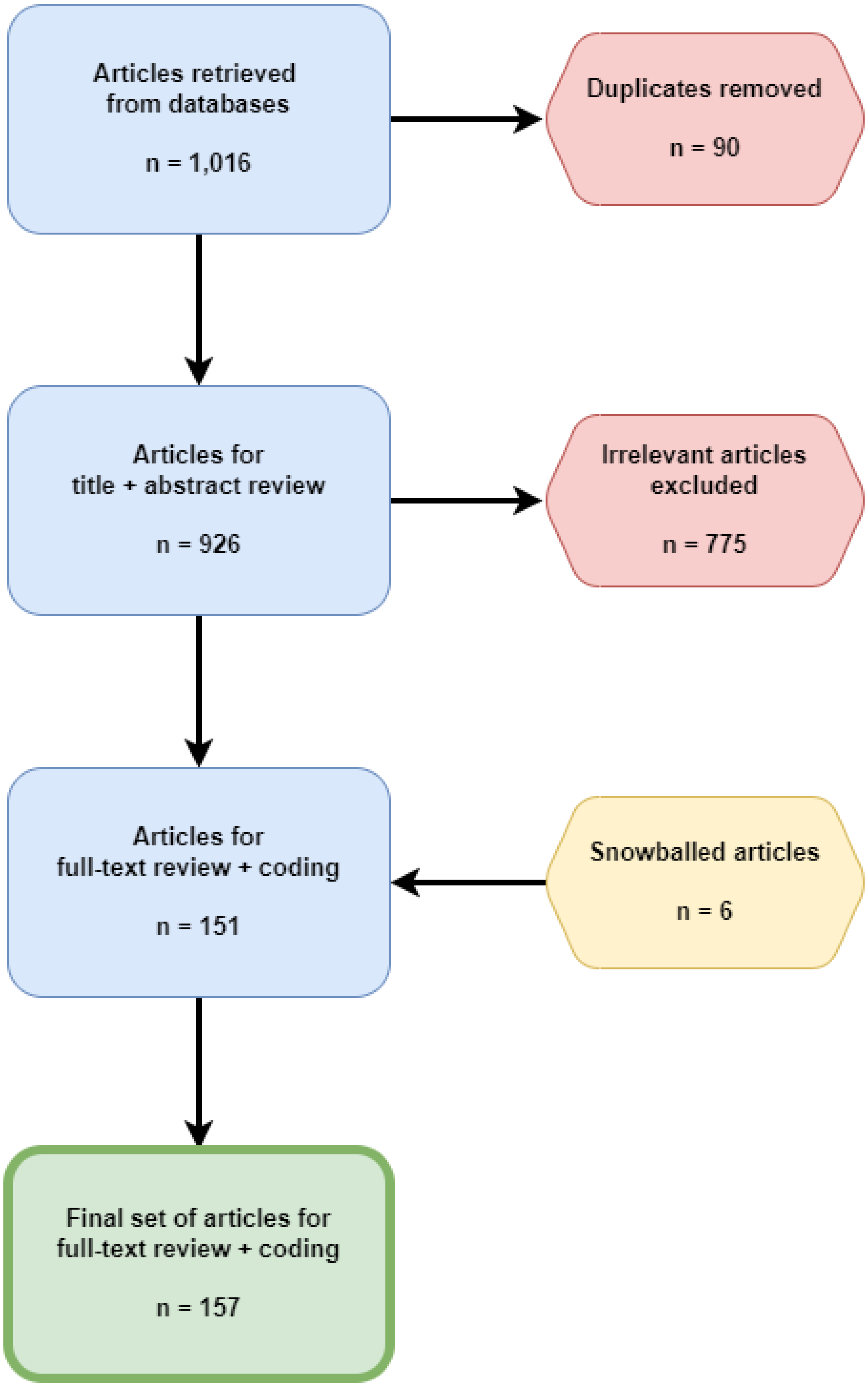
2.3 METHODS

First, we performed a scoping literature review to identify last mile challenges in vaccine delivery documented in English-language peer-reviewed and grey literature. The review was performed by a primary investigator (Ravi) and a co-analyst. The literature search was conducted in May 2020 and initially generated 1,016 documents (see Appendix A for details of the search strategy). We used Covidence to archive these documents, extract duplicates, and perform a preliminary scan of titles and abstracts. Documents were excluded if they did not address relevant vaccine delivery challenges, or if their primary focus was a high-income country, as defined by the World Bank (i.e., a country with a gross national income of USD$12,536 or more per capita). This process generated a preliminary list of 151 documents to undergo full review.

Next, we coded the documents using procedures articulated by Saldaña and Onwuegbuzie et al., with the purpose of identifying and organizing common themes to inform development of a holistic conceptual framework of last-mile challenges in vaccine delivery during outbreaks in LMIC settings.[44,45] The two members of the research team independently coded a randomly chosen subset of 20 “included” documents to generate a set of initial codes, synchronize coding processes, and construct a preliminary coding framework. Using NVivo 13 (QSR International), we then applied the preliminary coding framework to the full set of 151 documents, with new codes added iteratively as new themes were identified in the literature. Forward- and backward-snowballing were also used throughout the initial coding process to identify additional relevant documents not produced by the literature search; these documents (n=6) subsequently underwent full-text review and coding.

We then performed axial coding – a method for grouping or sorting codes identified during the initial coding phase – to refine the coding framework and articulate relationships between codes. We classified documents by methodology described, disease of focus, and area of focus (Table 1). We also classified documents by geographic focus (Table 2). Ultimately, 157 documents underwent full-text review, initial coding, and axial coding. On the next page, Figure 1 illustrates the inclusion and exclusion process.

Figure 2. Literature Review: Inclusion & Exclusion Process



We supplemented the scoping review findings with semi-structured key informant interviews (n=10) with purposively selected subject matter experts in vaccine policy and program implementation, vaccine manufacturing, epidemic response, health systems-strengthening, and vaccine delivery in LMICs and resource-constrained settings. Key informants were identified from the investigator's professional network and via forward snowballing (i.e., based on recommendations from prior interviewees). Interview questions were informed by findings from the initial and axial coding processes, and each interview was recorded and securely archived with the participant's permission. Preliminary findings from the scoping review were not shared with key informants, and interviews were conducted on a not-for-attribution basis to encourage unbiased, frank responses. During each interview, a member of the research team took detailed notes, which were subsequently coded with the same coding framework used in the scoping review to facilitate analysis across both data sources.

Finally, we adapted the approach laid forth by Earp and Ennett to construct a preliminary conceptual framework of last mile challenges in vaccine delivery encountered during outbreaks in LMICs (see Figure 3): we assembled an inventory of relevant variables identified from the scoping review and key informant interviews; mapped relationships between these variables, drawing linkages based on empirical evidence, theoretical evidence, and *a priori* knowledge; and narrowed the list of variables to a set that could be realistically addressed through epidemic preparedness and response measures.[46] This process resulted in four key framings of the last mile: geography, epidemiology, target populations, and health systems (see Findings: "Conceptualizing the Last Mile" for descriptions of each). Recognizing that there is considerable overlap between many of these challenges – and between the four framings themselves – we also transformed our axial codes into broad thematic categories that cross-cut these four framings, enabling us to further contextualize the last mile challenges identified in the literature and interviews. The thematic categories are governance and leadership, surveillance, workforce, program implementation, vaccine confidence, and population immunity; we also address challenges that cross-cut these categories. All relevant variables from the scoping review and interviews were included; however, because we did not identify other holistic frameworks of last mile vaccine delivery challenges in the literature, we were unable to validate our framework.

2.4 FINDINGS

First, we discuss the demographic profile of the documents selected for inclusion in the scoping review. Next, we present various conceptualizations of the last mile of vaccine delivery in LMICs, as gleaned from the literature and key informants, who are referred to by anonymized alphanumeric identifiers (e.g., Key Informant 1, "KI1"). Finally, we examine the various components in the conceptual framework presented in Figure 4, highlighting findings from the literature and key informant interviews supporting their inclusion.

2.4.1 Document Demographics

Prior to coding, each document selected for inclusion in the scoping review was classified according to type (peer-reviewed, grey, or news media); area of focus (barriers to vaccination, facilitators of or solutions to vaccination, barriers and facilitators, progress or gap analysis, or not applicable); geographic focus; disease of focus; and methodology used, if applicable. These classifications are summarized in Tables 1 and 2 and discussed briefly below.

The majority of documents reviewed were peer-reviewed articles (n=86; 54.8%) and comprised high-level reviews of vaccination efforts, policies, and/or practices (n=45; 28.7%). In terms of focus, most documents featured analyses of progress made toward resolving last mile challenges or remaining gaps (n=55; 35%), followed by analyses of barriers to vaccination (n=42; 26.8%), facilitators of vaccination (n=24; 15.3%), or both barriers and facilitators (n=30; 19.1%). Polio was the most common disease of focus, comprising 66.2% (n=104) of documents reviewed, followed by 14 (8.9%) documents that did not specify a disease and 10 articles (6.4%) that examined multiple vaccine-preventable diseases. The majority of documents focused on countries in Asia (n=37; 23.6%) and Africa (n=23; 14.6%); 52 documents (33.1%) covered multiple LMIC countries, while 37 (23.6%) did not specify a country of focus, choosing instead to describe last mile challenges in general terms. Only two documents apiece examining last mile challenges in Europe, Oceania, and the Middle East (1.3% each) met the inclusion criteria for this review. A comprehensive breakdown of document demographics is provided in Tables 1 and 2.

We also constructed a matrix to assess the distribution of methods described in the included documents against their respective areas of focus (Figure 2). The most commonly encountered documents among the 157 reviewed include policy statements analyzing progress made or gaps in immunization efforts (n=25), followed by reviews examining both barriers and facilitators of immunization (n=17). News media reports and field reports describing immunization efforts (n=22 and n=14, respectively) were the next most commonly encountered documents. Only 11 documents described multi-method or mixed-methods approaches to studying last mile challenges in vaccine delivery, while only two analyzed secondary data, three each featured impact assessments and in-depth interviews, and five reported survey results.

Table 1. Document Demographics

Document Type	Number of Documents (%)
Peer-Reviewed	86 (54.8%)
Grey	47 (29.9%)
News Media	24 (15.3%)
Total	157
Disease of Focus	
Polio	104 (66.2%)
Unspecified	14 (8.9%)
Multiple Diseases	10 (6.4%)
Seasonal Influenza	8 (5.1%)
Measles	5 (3.2%)
Cholera	5 (3.2%)
Pandemic Influenza	3 (1.9%)
COVID-19	2 (1.3%)
Pertussis	2 (1.3%)
Meningitis	2 (1.3%)
Lymphatic filariasis	1 (0.64%)
Diphtheria	1 (0.64%)
Total	157
Area of Focus	
Progress or Gap Analysis	55 (35%)
Barriers to Vaccination	42 (26.8%)
Both (Barriers + Facilitators)	30 (19.1%)
Facilitators of Vaccination	24 (15.3%)
Not Applicable	6 (3.82%)
Total	157
Methodology	
Review	45 (28.7%)
Policy Statement	28 (17.8%)
Not Applicable	23 (14.6%)
Field Report	13 (8.3%)
Multiple Methods	11 (7%)
Recommendations	10 (6.4%)
Commentary	5 (3.2%)
Program Evaluation	5 (3.2%)
Survey	5 (3.2%)
Impact Assessment	3 (1.9%)
In-Depth Interviews	3 (1.9%)
Cross-Sectional Study	2 (1.3%)
Secondary Data	2 (1.3%)
Focus Groups	1 (0.64%)
Modeling	1 (0.64%)
Total	157

Table 2. Geographic Focus of Documents Reviewed

Africa	Number of Documents (% of Total)
Nigeria	10 (6.4%)
DRC	2 (1.3%)
Ethiopia	2 (1.3%)
Malawi	2 (1.3%)
Angola	1 (0.64%)
Guinea-Bissau	1 (0.64%)
Kenya	1 (0.64%)
Mozambique	1 (0.64%)
Somalia	1 (0.64%)
South Africa	1 (0.64%)
South Sudan	1 (0.64%)
Subtotal	23 (14.6%)
The Americas	**Number of Documents (% of Total)**
Brazil	1 (0.64%)
Haiti	1 (0.64%)
Subtotal	2 (1.3%)
Asia	**Number of Documents (% of Total)**
Pakistan	21 (13.4%)
China	5 (3.2%)
India	4 (2.5%)
Afghanistan	3 (1.9%)
Cambodia	1 (0.64%)
Indonesia	1 (0.64%)
Sri Lanka	1 (0.64%)
Thailand	1 (0.64%)
Subtotal	37 (23.6%)
Europe	**Number of Documents (% of Total)**
Turkey	2 (1.3%)
Subtotal	2 (1.3%)
Middle East	**Number of Documents (% of Total)**
Syria	1 (0.64%)
Iran	1 (0.64%)
Subtotal	2 (1.3%)
Oceania	**Number of Documents (% of Total)**
Papua New Guinea	1 (0.64%)
Vanuatu	1(0.64%)
Subtotal	2 (1.3%)
Other	**Number of Documents (% of Total)**
Multiple Countries	52 (33.1%)
Unspecified	37 (23.6%)
Subtotal	89 (56.7%)
TOTAL	**157**

Figure 3. Methodological and Reporting Approaches to Examining Last Mile Challenges in Vaccine Delivery and Uptake During Outbreaks in Low- and Middle-Income Settings

METHOD OR FORMAT OF REPORTING	AREA OF FOCUS					
	Progress or Gap Analysis	Barriers	Facilitators	Barriers and Facilitators	Other	TOTAL
Commentary	0	2	1	2	0	**5**
Cross Sectional	0	2	0	0	0	**2**
Field Report	4	4	2	3	1	**14**
Focus Groups	0	0	1	0	0	**1**
Impact Assessment	2	0	1	0	0	**3**
In-Depth Interviews	0	2	1	0	0	**3**
Media Report	10	7	4	0	1	**22**
Modeling	0	0	0	0	1	**1**
Multiple Methods	1	6	1	2	1	**11**
Policy Statement	25	0	3	0	0	**28**
Program Evaluation	1	1	1	2	0	**5**
Recommendations	1	2	4	3	0	**10**
Review	10	13	5	17	0	**45**
Secondary Data Analysis	1	0	0	0	1	**2**
Survey	0	3	0	1	1	**5**
TOTAL	**55**	**42**	**24**	**30**	**6**	**157**

Figure 4.
Conceptual Framework of Last Mile Challenges in Vaccine Delivery & Uptake During Outbreaks in LMICs

LAST MILE DIMENSION	THEMATIC CATEGORY					
	Governance & Leadership	**Workforce**	**Surveillance**	**Program Implementation**	**Vaccine Confidence**	**Population Immunity**
Geography	• Lack of jurisdiction over contested terrain	• Threats to physical safety • Maldistribution of vaccination workforces • "Brain drain"	• Monitoring borders • Environmental surveillance	• Seasonality and climate • Topography and terrain • Cold chain preservation	• Long distance from health facility catchment area • Inaccessible vaccination sites	• Atypical reservoirs • Multiple reservoirs
Epidemiology	• Waning political will • Donor fatigue • Competing priorities	• Integrating epidemic responders into routine health workforces	• Diminishing sensitivity • Unreliable reporting • Monitoring populations at or above critical community size • Asymptomatic case detection	• Pathogen reintroduction due to poor program coordination	• Accumulation of susceptible individuals	• Emergence of new pathogen lineages
Target Populations	• Mistrust of public health institutions, leaders, and decision-makers	• Limited vaccination referrals • Linguistic & cultural barriers • Public mistrust of health workers	• "Hidden," mobile, undocumented, stigmatized populations • Identifying remaining target populations for vaccination	• Risk communication • Community engagement	• Hesitancy & refusal • Misinformation & disinformation • Adverse events	• Waning immunity • Low per-dose efficacy
Health Systems	• Weak accountability mechanisms	• Insufficient refresher training & supervision • Diminishing morale	• Poor health information management • Coverage measurement challenges • Conducting genomic surveillance	• Poor microplanning • Vaccine forecasting challenges	• Failure to account for community priorities • Demand generation and forecasting	• Dosing regimens

CROSS-CUTTING CONSIDERATIONS

- **Funding:** Insufficient funds to sustain vaccine manufacturing & purchasing, stockpiling, staffing vaccination programs, and monitoring target populations
- **Quality assurance:** Medical errors, absentee vaccinators, unpaid staff, poor campaign quality
- **Integration:** Insufficient resources and public demand to support integration of vaccination into broader health systems

2.4.2 Conceptualizing the Last Mile

Based on findings from the key informant interviews and literature, we synthesized four ways to conceptualize the last mile of vaccine delivery and uptake during outbreaks in LMICs (hereinafter referred to as "the last mile"). These conceptualizations frame the last mile primarily in terms of geography, epidemiology, target populations for vaccination, and health system functioning. We discuss these framings below.

2.4.2.1 Geography

The last mile challenges posed by space and place often manifest as physical barriers to vaccination. As KI1 stated, "[The last mile] is synonymous with the hardest to reach geographically, or urban areas where populations are hard to serve or not well-documented." KI2 defined the last mile in LMICs by contrast with the last mile in HICs: "In the U.S. or another richer country, I think [the] last mile is much more mechanical because it involves more traditional logistics – trucks, boxes, storage, etcetera…However, the last mile in LMICs is totally different. We talk bicycles and baskets. It's like comparing apples and oranges." In this vein, the literature cited remote or rugged terrain, long distances between households and health facilities, absence of transportation, seasonal trends (e.g., heavy rains, extreme heat), and poor climate adaptation (e.g., lack of reliable power to maintain cold chains) as common geographic barriers impeding vaccine delivery and uptake.[47–49] We refer to this collective framing of challenges as "the geographic last mile" in this investigation.

2.4.2.2 Epidemiology

Though its name might suggest otherwise, the last mile is not defined by geography alone. Klepac et al. define the last mile (or “endgame”) as “the final stages of an elimination or eradication programme, when disease is still circulating, although at much reduced levels (i.e., during the epidemic tail).”[8] We refer to this framing as “the epidemiological last mile.” Klepac et al. note that this stage differs from earlier epidemic phases due to accumulation of susceptible, unvaccinated individuals who may still be vulnerable to infection by low levels of the circulating pathogen in question. When the number of susceptible individuals surpasses a given threshold – especially in settings where a pathogen is reintroduced after having previously been eliminated – disease incidence could resurge and spark an outbreak.[8] The epidemiological last mile is exemplified perhaps most clearly by the ongoing international effort to eradicate polio.[50] Though global polio incidence has been reduced by 99% between 1988 and 2018, localized clusters of wild poliovirus type 1 persist in Pakistan and Afghanistan, where reaching unvaccinated populations remains a major challenge.[51–53] Concurrently, suboptimal immunization coverage has given rise to outbreaks of circulating vaccine-derived poliovirus in both countries, as well as in Yemen and across sub-Saharan Africa.[54] Similar challenges were encountered during the final stretch of the Global Smallpox Eradication Program, wherein vaccinators struggled to identify lingering cases, isolate infected individuals, and vaccinate remaining susceptible persons in a small handful of countries.[55]

2.4.2.3 Target Populations

In addition to geography and epidemiology, the last mile is sometimes conceptualized in terms of specific populations targeted for vaccination, which we refer to herein as “the target population last mile.” This framing elicited broad consensus among the key informants, many of whom agreed that routine and emergency vaccination efforts are most likely to miss so-called “last mile communities,” which are typically characterized by concentrated societal disadvantage. KI3 observed, “Increasingly, ‘last mile’ means lack of access and vulnerability such as seeing challenges in urban slums. It used to be the rural last corner of the world, but it can sometimes be easier there than [with] invisible vulnerable groups that can be harder to reach and see…We used to think about last mile as the most difficult area to reach – it was a logistics challenge. Now it’s an identification and connection issue instead.” KI4 agreed, noting, “It’s people who have the least access to health services, which is often also the people who are most vulnerable…It’s about getting the vaccine to them but also about the equity level where these are the people impacted the most.”

In the literature reviewed, unvaccinated children under 5 were among the most commonly discussed last mile target populations. Other target groups highlighted in the literature include highly mobile populations, such as migrants, asylum-seekers, stateless persons, and undocumented persons; the elderly; pregnant individuals; and those with high-risk occupations, such as healthcare workers. Ozawa et al. further note that defining the last mile in terms of reaching disadvantaged, marginalized, or otherwise hard-to-reach target populations implicitly underscores the importance of dismantling inequities in vaccine delivery and uptake.[56–58]

2.4.2.4 Health Systems

Finally, both the literature and the key informant interviews suggest that the last mile may also be conceptualized in terms of health system structure, performance, and public demand for health services, which we describe herein as “the health system last mile.” KI5 shared, “If you don’t have someone presenting to the clinic, [and] the health system has to proactively reach out to get data and respond, then that’s the last mile. Any issue where people aren’t proactively seeking care in certain ways because the barriers are too high or because the care doesn’t exist – that’s the last mile.” Several studies reported that public demand for integrated immunization programs (that also provide health services prioritized by target populations) is often a precursor to vaccine uptake and coverage.[59] KI6 also framed the last mile in terms of health system outcomes, explaining,

> “I think typically the last mile is referring to hitting a saturation point of vaccine coverage, so that would be the last groups to help you hit your target…For example, there’s been a flatline on flu shots for ten years [in the United States, at 55-60%]. We’ve removed cost by making it free, we’ve made it convenient with pharmacies everywhere, and we’ve bumped up reimbursement from providers… Saturation is [when] you’re stuck because you’ve already released as many barriers as possible.”

Plateauing coverage, in turn, signals that immunization efforts are failing to serve the least-reached target populations. A vaccine demand deficit among these populations could subsequently act as a rate-limiting step to increasing vaccine uptake and curbing disease incidence. Several documents reviewed suggested that targeted demand creation interventions in LMICs – such as improving ease of vaccine access, offering incentives for vaccination, and proactive community engagement – could play an important role in offsetting the demand deficit in last mile contexts.[60,61]

Below, we summarize the scoping literature review and key informant interview findings from each thematic category in the conceptual framework: governance and leadership, health workforce, surveillance, program implementation, vaccine uptake, population immunity, and cross-cutting considerations. Within each thematic category, we disaggregate findings by each of the aforementioned last mile dimensions (geography, epidemiology, target populations, and health systems). While these dimensions and thematic categories are not always mutually exclusive, we nevertheless posit that this framework could serve as a useful typology of last mile challenges that informs and supports planning around vaccine delivery efforts during outbreak response.

2.4.3 Governance and Leadership

Both the literature and the key informant interviews affirmed the importance of strong leadership, sustained political will to continue support for immunization efforts, and effective oversight of immunization programs. Our findings also underscore the importance of public accountability for programmatic successes and failures among decision-makers and lawmakers in government, public health institutions, and non-governmental organizations working to overcome last mile challenges.

2.4.3.1 Geography

Critical governance challenges emerge in the context of the geographic last mile. For example, when governments, particularly those operating in weak or fragile states, lack jurisdiction over contested terrain due to conflict or other forms of political instability, immunization program implementation grows increasingly complex. In conflict zones and along porous state borders, for instance, vaccination bans enforced by the Taliban and Boko Haram have enabled continued poliovirus transmission in Pakistan and Nigeria, respectively.[43,62–64] Drawing from experiences in Guinea-Bissau, Ferrinho et al. further note that frequent changes in government leadership due to civil war resulted in the dissolution of the national focal points for Gavi, the Vaccine Alliance's programs and health systems strengthening.[65] Paradoxically, endorsement of vaccination from political leaders – generally a positive development – could undermine vaccination efforts in conflict-affected settings. In 2010, for example, it was reported that then-President Hamid Karzai's support for vaccination campaigns in Taliban-controlled areas of Afghanistan had detrimental effects on polio eradication activities.[64]

2.4.3.2 Epidemiology

In the context of the epidemiological last mile, waning political will among policymakers constitutes another governance challenge wherein dwindling case numbers could discourage continued investment in disease mitigation activities. Von

Seidlein et al., for example, underscore the importance of political support in achieving high vaccination coverage via supplemental immunization activities (SIAs) in epidemic settings.[66] Ozawa et al. also note that political will often translates into tangible health outcomes, describing how catchment areas with weak social and political commitment to vaccination are often harder for immunization programs to reach, and underscoring the need for more robust measures of such commitment.[47] However, KI3, discussing the ongoing COVID-19 pandemic, remarked:

> "I don't know how to sustain political will – there's not always rhyme or reason. Polio and smallpox make sense due to the massive impact. But why does one donor decide to eradicate guinea worm? It's a target and doable, so there's ego and being able to say you did it…People pick up pet projects and pet diseases. But it has to be semi-achievable. [There are] other pressures like trade and travel [with] yellow fever, so there's massive pressure to keep that under control. I think there's a range of reasons from heartstring arguments to compelling arguments to being able to just say that you eliminated something."

This challenge becomes especially salient in the context of disease elimination and eradication efforts, which often demand significant political will at regional and global scales. In this vein, Grassly reports that the success of GPEI relies heavily on dedicated advocacy through Rotary International and UNICEF, which proactively secures financial commitments from heads of state and regional political bodies, as well as support for vaccination activities from local religious and political leaders.[62] High-level political commitment and advocacy have proven similarly consequential in ongoing measles and rubella elimination efforts, especially as SIAs are increasingly co-opted as vehicles for strengthening routine immunization programs.[67,68] On this issue, von Seidlein et al. further echo the importance of advocacy, observing that "the difference between cholera and influenza vaccination campaigns is not the scale of the logistical challenge but the absence of vigorous advocacy for populations at risk for cholera."[66]

In addition to dissipating political will, donor fatigue may present further challenges during the epidemiological last mile, especially as other programmatic priorities compete for limited resources. Klepac et al. note that as case numbers fall, the costs associated with vaccinating remaining susceptible individuals – often belonging to the remotest or most marginalized populations – increase significantly.[8] As costs accumulate, however, donors grow fatigued and may elect to withdraw financial support from immunization programs, which could spark case importation, reemergent infections, and community transmission.[8] Critically, Klepac et al. also note that last mile obstacles encountered during elimination or eradication efforts could prolong program timelines, potentially jeopardizing political and philanthropic support for future disease control initiatives.[8] In some cases, donor preferences for prioritizing "low-hanging fruit" (i.e., short-term programmatic successes) could further prolong disease control, elimination, or eradication efforts in the epidemiological last mile. On this point, Ganapathiraju et al., quoting Taylor, write regarding GPEI, "When a programme prefers the political safety of educational problems rather than the wider problems of governance and the distribution of wealth and well-being, such as the polio eradication programme, the global consequences can be that it will find itself blocked in the last mile of a long race."[64,69]

Power dynamics between donors and program implementers also play an important role navigating the epidemiological last mile. Yehualashet et al., for example, describe WHO's approach to mobilizing donors and resources for polio elimination efforts in Nigeria between 2008-2015, an exhaustive effort involving an internal reorganization of WHO's country office in Nigeria to form a dedicated donor relations team; regular donor mapping activities; business development and proposal writing; and public messaging to amplify donor contributions.[70] Notably, donors wield considerable influence in these engagements, from appraising proposed projects and specifying areas of programmatic focus, to determining funding ceilings and meeting with media and state leaders during field missions.[70] In the context of measles and rubella vaccination, Orenstein et al. further note that donor preferences often dictate fiscal flows, which in turn shape programmatic objectives and outcomes. Many donors, for example, prefer to direct funds to Gavi, the Vaccine Alliance – a single agency supporting a range of antigens – which funds measles morbidity and mortality reduction, but not elimination or eradication. As countries transition away from Gavi support, diminished access to measles-specific funds could leave them vulnerable to future outbreaks.[68]

2.4.3.3 Target Populations

Governance and leadership are also essential to building public trust – a cornerstone of reaching last mile populations – in the institutions tasked with implementing immunization programs during an outbreak. Rockers et al. note that public healthcare systems are highly visible, primary interfaces for citizen-government interaction; consequently, positive experiences within a health system strengthen public trust in government, which in turn confers greater legitimacy upon public institutions.[71] Ozawa et al. build on this idea, proposing that trust in vaccination and trust in health systems writ large influence each other via a mutually reinforcing feedback loop, and noting that poor vaccine readiness – especially during or after an acute health emergency – could disincentivize health system utilization and foment distrust.[72]

The erosion of public trust comes at a high cost to immunization programs in last mile settings. In 2011, for example, a Pakistani physician coordinated a fake hepatitis B vaccination campaign that allegedly enabled U.S. intelligence operatives to locate Osama bin Laden's compound in Abbottabad.[61] Subsequently, Pakistanis and Taliban militant leaders expressed mistrust of health workers and aid workers, leading to polio vaccination bans in high-risk regions and targeted violence against these workforces; health experts also cite the incident as a catalyst of polio resurgence in the region.[73]

2.4.2.4 Health Systems

The health system last mile also poses critical governance challenges, primarily in the form of weak accountability mechanisms within vaccination programs and campaigns. In last mile contexts, donors and governments bear the brunt of responsibility for funding, implementing, and overseeing such activities to ensure they are carried out with fidelity and timeliness. Continuous monitoring, evaluation, and learning activities support efforts to track achievement of programmatic objectives, appropriate management of funds and personnel, and alignment with donor and community priorities. Describing polio vaccination efforts in Afghanistan, Simpson et al. note that the absence of such mechanisms has hindered timely achievement of programmatic objectives.[53] Similarly, GPEI has identified accountability for vaccination program quality as a major barrier in Pakistan – a remaining battleground of polio eradication– where a lack of district-specific approaches to vaccination and accountability among local government leaders for program performance has hindered progress.[74] In an effort to improve accountability at community levels, the Pakistani national government implemented enhanced surveillance to detect remaining viral reservoirs, proactively monitored poor-performing districts, and strengthened engagement with and oversight of provincial- and district-level health leaders.[75] The Indian Academy of Pediatrics also recommends that village leaders (*panchayats*) assume responsibility for suboptimal vaccination coverage in settings with low levels of health literacy.[76] Klepac et al. corroborate the need for locally specific strategies to strengthen program accountability to the communities in which they operate; they cite the failed Global Malaria Eradication Programme, which suffered from limited community involvement and relied on a highly rigid program structure that proved difficult to implement across diverse malaria-endemic regions. By contrast, the flexibility of the smallpox and rinderpest eradication programs – combined with their proactive involvement of local community members – were instrumental to their ultimate success.[8]

Though not a part of this scoping review, Gebre describes these and other active disease eradication programs targeting yaws, guinea worm, and malaria, highlighting factors contributing to their successes and failures.[77]

2.4.4 Health Workforce

In addition to governance challenges, the scoping review highlighted last mile hurdles relating to building, deploying, and sustaining robust immunization workforces, including physicians, nurses, and community health workers.

2.4.4.1 Geography

The importance of workforce availability and distribution was a recurrent theme with respect to the geographic last mile, with health worker attrition, unsafe working conditions, and understaffing being cited as major barriers to immunization program implementation. Chaignat et al., for example, report that the death of numerous healthcare workers in the 2005 Indian Ocean tsunami and the subsequent diversion of surviving workers to various post-disaster health interventions hindered routine measles vaccination campaigns in Indonesia.[78] Zurn et al. also note that geographic imbalances in health workforce distribution – primarily in the form of low physician density in rural versus urban areas – present further challenges to health service delivery.[79] Additionally, the literature described war and conflict as catalysts of so-called health worker “brain drain” – the exodus of health workers in search of higher standards of living, safer work environments, and political stability.[80,81] Beyond their threats to the personal safety of health workers, war and conflict can also create physical barriers to last mile vaccine delivery through bans on home visits, blocked roads, and the destruction of critical infrastructure needed to preserve cold chains.[47,82,83]

2.4.4.2 Epidemiology

As case numbers dwindle during an outbreak, decision-makers must also consider whether or how to integrate vertical programs and outbreak responders – including vaccinators – into systems for delivering routine care. The challenge of integration has figured prominently in past and current disease eradication efforts, as well as in SIAs for measles and polio. Bhutta describes, for example, how vertical polio programs divorced from horizontal systems for routine immunization have given rise to programmatic inequities in resource allocation, staffing, and financial support.[84] In turn, chronically under-resourced horizontal programs – whose staff are often poorly incentivized for routine service provision and frequently diverted to support time-sensitive vertical efforts – could actually undermine efforts to increase vaccination coverage, thereby risking disease reintroduction into previously case-free regions.[84,85] This phenomenon – wherein programmatic objectives supersede systems-level priorities – has been described by Hitchins et al. and Peters et al. as the "Develop-Distort Dilemma."[86,87] KI4 also suggested,

> "Maybe supplemental [immunization activities] would be great for a community. But maybe you send doses with health workers and also address the bigger health burdens in that setting. We can prioritize resources for vulnerable

> communities without specifying how those resources are used. This is all contextual and dependent on the type of health system, legality, and whether a public health emergency is happening. But from an ethics and public health perspective, that's what I think is advisable when there's dwindling case numbers."

In this vein, Fields et al. report that in 2008, measles SIAs conducted across 17 African countries concurrently provided over 57 million doses of vitamin A supplements, 24 million doses of deworming medication, and 3.4 million insecticide-treated nets.[67] Operationalizing these so-called "diagonal" or "perpendicular" approaches in the epidemiological last mile could offer a viable path forward for transitioning epidemic immunization workforces into routine health programs.

2.4.4.3 Target Populations

Notably, these examples also illustrate how maldistributed workforces and conflict could exacerbate vaccine delivery challenges in the target population last mile. For example, the literature highlighted several challenges relating to health worker knowledge, competence, motivation, and training. In some cases, health workers have demonstrated limited understanding of the benefits, efficacy, and safety of vaccines, or lacked training in safe injection practices.[88,89] In others, they might refuse to refer patients for immunization due to missing vaccination cards, impose false contraindications to vaccination, or discriminate against patients of marginalized backgrounds (e.g., LGBTQ+ populations).[72,88,90] Such practices, in turn, erode trust among target populations. The literature broadly underscored the value of routine and refresher training for health workers staffing SIAs, highlighting essential foci of training curricula: adverse events following immunization, vaccine storage and handling, injection techniques, relevant contraindications, safety and benefits of vaccination, and patient follow-up.[85,91,92]

2.4.4.4 Health Systems

Health worker fatigue and deteriorating motivation are health system factors that often impede the success of vaccination programs. Dasgupta et al. report that low morale was a barrier to accelerating polio vaccination efforts in high-risk districts across India, but its root causes appear to vary across settings.[93] For example, Ferrinho et al. attribute low morale to the inability of some governments to pay health workers in a timely manner, while Fields et al. and Griffiths et al. highlight differences in monetary incentives between SIA and routine immunization workforces as a source of health worker discontent.[59,65,67] Additionally, the literature highlighted insufficient refresher training as a barrier to maintaining health workforce competence: though such training is often provided during measles SIAs, for example, post-SIA training reinforcement has proven challenging.[67,85]

2.4.5 Surveillance

Successful vaccine forecasting, delivery, and uptake depend on accurate assessments of disease burden and transmission during an outbreak. As such, surveillance plays a critical role in supporting vaccine delivery.

2.4.5.1 Geography

In some cases, geography exacerbates challenges associated with monitoring vaccine-preventable diseases in last mile communities – a phenomenon exemplified by ongoing polio eradication activities in Pakistan and Afghanistan, which share a highly porous land border, the Durand Line. One official crossing point, Chaman/Spin Boldak, reports that as many as 30,000 persons per day cross the border; annually, it is estimated that as many as 1 million children per year cross the Durand Line.[94,95] Limited capacities to monitor the movement and vaccination status of these children has enabled continued cross-border transmission and poliovirus circulation in both countries.[96] Uzoma et al., describing polio elimination activities in Borno State, Nigeria, further corroborate the need for tracking mobile populations and using those data to inform vaccination strategies and sustain population coverage.[97] Finally, the polio literature covered in this scoping review frequently cited environmental surveillance as a critical surveillance challenge in the geographic last mile. Lopalco et al. note, too, that circulating vaccine-derived poliovirus may persist in environments with poor sanitation and among populations with suboptimal polio vaccination coverage.[98]

2.4.5.2 Epidemiology

The literature described a range of challenges associated with conducting surveillance in last mile contexts, particularly in the epidemiological last mile. Here, Klepac et al. observe that detecting cases – especially in asymptomatic persons or long-term shedders – becomes significantly harder as case numbers fall. Citing the smallpox eradication program, they also note that routine passive surveillance methods may not suffice during epidemic tails, underscoring the need for active approaches to case detection.[8] In turn, diminishing sensitivity of case-based surveillance systems during the epidemiological last mile can undermine last mile vaccination strategies that depend on robust case investigation, such as ring vaccination.[99] Grassly et al. and Kew et al. also affirm the value of robust environmental monitoring in bolstering case-based surveillance sensitivity in last mile contexts, with GPEI reporting that sampling sewage has enabled detection of low-level poliovirus circulation even absent reported cases of acute flaccid paralysis.[49,62,74] However, financing, staffing, and implementing robust environmental surveillance practices remains difficult in many resource-constrained settings.[100–102]

2.4.5.3 Target Populations

Because lingering infections are often concentrated among hard-to-reach, remote, or otherwise disadvantaged populations, surveillance challenges in the epidemiological last mile interface closely with those encountered in efforts to deliver vaccines to last mile communities. KI3 reflected on the role of stigma, sharing, "In Uganda, where [LGBTQ+] populations are targeted arrested and killed, when we ask teams on how you include them in surveillance and other things, teams just say there aren't any homosexuals in Uganda. So, they get missed during the last mile…Those communities are invisible and try to be invisible on purpose." Haydon et al. also describe the role of critical community size (CCS) in monitoring target populations: "the minimum size of a closed population within which a pathogen can persist indefinitely."[103] Target populations below CCS can eliminate a given pathogen by isolating themselves (i.e., "ring-fencing"), but those above remain at risk for continued disease transmission. Therefore, last mile surveillance systems operating in LMICs must cover appropriate epidemiological units: those with populations above CCS, that are likely to interact with other populations.[8]

2.4.5.4 Health Systems

The literature highlighted several information management challenges manifesting in the health system last mile. Wagner et al., for example, consider the utility of vaccination cards in tracking childhood vaccination status, highlighting challenges in updating, interpreting, and preserving these documents among mobile, remote, displaced or otherwise hard-to-reach populations.[90] With limited or unreliable documentation of vaccination status, immunization program planners may encounter challenges in monitoring at-risk populations for emergent cases of disease or allocating limited supplies of vaccine. Surveillance, workforce, and information management hurdles may also complicate efforts to measure immunization coverage, the primary metric of success for many routine and emergency vaccination efforts. KI4 observed, "I think the more disaggregated data, the better. That's how you find who is being addressed and who is not. [Coverage] is one way to do it. But it's insanely hard to get disaggregated data, especially in places that rely on on-paper reporting…Health systems that compensate and employ folks that do that, they should design interventions and plan programs to address equity and coverage."

The ability to conduct genomic surveillance is also essential to identifying potential threats to immunization coverage in the last mile, and genomic surveillance is a crucial tool for monitoring and sustaining population immunity at all points during the vaccination program life cycle. Warmbrod et al. define genomic surveillance as a branch of genetic epidemiology that involves sampling, sequencing, and comparing pathogen isolates from infected persons to identify mutations in the pathogen's genome.[104] As part of its ongoing response to the COVID-19 pandemic, for example, the U.S. Centers for Disease Control and Prevention routinely analyzes genetic sequence data to identify viral variants with enhanced transmissibility or virulence, or decreased susceptibility to existing prophylactic measures (i.e., vaccinations) and treatments.[105] Describing the process of collecting laboratory samples in sub-Saharan Africa, however, KI5 shared, "There are small machines you can take in a backpack, but keeping the reagents cold is so tough. We just can't do genomic surveillance at the last mile and that makes strain selection a real concern." Resource constraints in such settings thus weaken capacities to identify mutations that, in turn, could trigger new outbreaks or cause breakthrough infections in vaccinated individuals.

2.4.6 Program Implementation

Durlak defines program implementation as the process of putting a proposed program or intervention into practice.[106] MacDonald et al. later noted that "implementation is 'the Achilles heel of innovation' and is often defined as an evidence-to-practice gap in which successful implementation of evidence-based interventions is fraught with challenges."[107] Here, we discuss logistical, managerial, administrative, and other programmatic hurdles encountered while carrying out vaccination efforts during the last mile of outbreak response in LMICs. Unsurprisingly, the last mile is often fraught with such challenges – which, if left unresolved, impede vaccine delivery and uptake.

2.4.6.1 Geography

Logistical barriers such as cold chain preservation often hamper program implementation in last mile contexts.[108] Given that many vaccines lose potency over time – and that such loss in potency is temperature-dependent – cold chain preservation is essential to the success of vaccine delivery programs. However, the geographic last mile often poses unique seasonal, topographical, and climatological barriers that risk compromising cold chains. Describing a measles outbreak in Ethiopia, for example, Belda et al. report that the absence of working refrigerators, challenging topography, and long distances between health centers and target populations could diminish vaccine potency – in turn resulting in low vaccination coverage in remoter populations.[48] Similarly, Ozawa et al. cite mountainous regions, wetlands, and islands as topographical barriers to vaccine program implementation, alongside seasonal challenges such as heavy rain and flooding.[47]

2.4.6.2 Epidemiology

In addition to these geographic hurdles, coordination of activities within and across vaccine delivery programs can trigger further challenges in the epidemiological last mile. For example, so-called “mop-up” campaigns – wherein vaccinators focus on high-risk individuals missed by routine “keep up” campaigns or periodic “catch up” and “follow up” campaigns – are often deployed in late-stage elimination or eradication efforts, with the goals of curbing transmission and preventing pathogen reintroduction.[109] Describing polio vaccination activities in South Africa, Blecher et al. note that poorly synchronized implementation of mop-up campaigns led to case importation into areas previously considered virus-free.[109] The global polio vaccine “switch” – wherein the trivalent oral polio vaccine was withdrawn from use and replaced with a bivalent vaccine to prevent emergent cases of circulating vaccine-derived poliovirus type 2 – is another illustrative example of robust global coordination during the epidemiological last mile.[110]

Cross-border epidemic threats further underscore critical vaccine program implementation challenges during the epidemiological last mile. Reporting on polio eradication efforts in South Asia, the Horn of Africa, and the Lake Chad region, for example, WHO highlights the need for international partners to coordinate cross-border activities to better reach vulnerable, highly mobile populations – for example, by synchronizing vaccination campaigns, taking measures to combat polio fatigue, conducting joint planning, and sharing surveillance data.[111,112] Describing parallel challenges associated with curbing a multi-country diphtheria epidemic in the former Soviet Union, Vitek and Wharton also highlight several factors supporting vaccine program coordination across borders, including a well-trained health workforce, networks of primary health and public health centers, and international assistance to shore up gaps in vaccine and antitoxin availability, improve cold chain management, and accelerate social mobilization.[113]

2.4.6.3 Target Populations

Risk communication and community engagement emerged from the literature as salient implementation challenges in the target population last mile. Klepac et al., describing late-stage eradication efforts, report that rumors and other negative messaging around vaccination can lead to greater perceived risks of adverse events, vaccine refusal, loss of community buy-in and cooperation, and even withdrawal of political commitment and donor support for vaccination programs.[8] Echoing these findings, Saint-Victor and Omer report that media coverage of epidemic trends correlates closely with epidemiological trends of disease mortality; thus, as deaths and disease incidence fall, so too does messaging around the importance of vaccination.[43] Such trends further underscore the urgency of robust community outreach in ensuring successful vaccine program implementation. In its 2019 emergency plan for eradicating polio, for example, Pakistan's National Emergency Operations Center asserted, "Community engagement remains the most critical asset for closing gaps in the core reservoirs. Direct or hidden refusals associated with misconceptions and religious or other beliefs are the primary reasons for the non-vaccination of remaining missed children in these areas."[114]

2.4.6.4 Health Systems

Critical challenges encountered during the health system last mile further impede vaccine delivery and uptake. Inadequate microplanning for immunization service delivery, for instance, was cited widely across both the literature and key informant interviews as a major last mile barrier to vaccine program implementation. Yehualashet et al. write that microplan development underpins successful, high-quality vaccination campaigns, reporting that improved microplans in Nigeria contributed to a 17% reduction in the proportion of wards with children missed by polio vaccination campaigns.[70] KI8 also shared, "If the microplan is no good, then we're in trouble. That brings in the vaccine, cold chain, and supply-demand. Many countries don't pay enough attention to this at all." Similarly, KI9 echoed the importance of developing integrated microplans addressing communication needs, operational considerations, and vaccine management, stating, "Microplans need to be tailored to the target community. There should not be one plan for the whole country." When asked why microplanning remains such a challenge in epidemic contexts, KI3 described microplanning as "one of those things that's less sustainable because surge teams bring it in and take it when they leave." In some contexts, the literature also documented comparatively weak microplanning practices for routine immunization program implementation versus SIAs. Commenting on polio eradication efforts, for example, the Indian Academy of Pediatrics cited an absence of microplanning for routine immunization as a driver of poliovirus reintroduction into disease-free districts, further criticizing SIAs for diverting resources, time, and personnel from routine immunization programs.[76]

2.4.7 Vaccine Confidence

The literature and key informant interviews indicated that vaccine confidence presents a broad range of social, behavioral, and access-related challenges during the last mile. In a departure from many of the previously discussed thematic categories and challenges – which largely center around supply-side forecasting, procurement, and delivery considerations – vaccine confidence challenges often reflect demand-side barriers. We chose to include vaccine confidence as a thematic category in our framework to illustrate how challenges emerging at the point of care (e.g., vaccine hesitancy, skepticism, or refusal) can derail efforts to improve coverage and protect population health.

2.4.7.1 Geography

A number of geographic challenges may undermine vaccine confidence in last mile contexts. As previously discussed, long distances between vaccines and their intended target populations risk reducing vaccine potency; such distances may also disincentivize populations from seeking vaccinations in the first place. The challenges of space and place also manifest in ways beyond distance, such as when campaigns establish vaccination sites in locations that are inconvenient or difficult to reach, potentially unsafe, unfamiliar, or uncomfortable, or otherwise inaccessible to target populations.[47,115,116]

2.4.7.2 Epidemiology

Further challenges associated with diminishing vaccine confidence also emerge in the epidemiological last mile, wherein falling case numbers could lead to pockets of unvaccinated persons, a phenomenon that distinguishes the “endgame” of infectious disease elimination from “middle game” efforts.[8] In this vein, various studies describe how low, post-campaign rates of disease circulation and transmission – abetted by the failure of routine programs to sustain post-campaign immunization coverage – leads to the accumulation of susceptible, unvaccinated individuals. Omer et al. further note that falling disease incidence could reduce public risk perceptions of the disease in question; this, in turn, could further disincentivize vaccination and contribute to an accumulation of susceptible persons.[117] Vaccination programs could also catalyze shifts in the distribution and characteristics of emergent cases during the epidemiological last mile. Measles vaccination campaigns that target young children, for example, could lead to an increase in the average age of infection as susceptible individuals are concentrated in older cohorts.[8] This feature of the epidemiological last mile may also necessitate important changes in vaccine program implementation, such as modified surveillance approaches to monitor new at-risk populations and new risk communication strategies to reach said populations.

2.4.7.3 Target Populations

Risk perception challenges also shape vaccine confidence among last mile target populations. Studying Thai adults’ willingness to obtain a seasonal influenza vaccine, for example, Payaprom et al. report that some study participants would only seek a vaccination if there was a local outbreak posing a direct threat to their health.[118] Wu et al., describing the 2009 H1N1 influenza pandemic in Beijing, echo this finding, noting that study participants reported low perceptions of personal risk and did not expect to contract influenza; this perception was presented as the primary barrier to vaccination.[119] Conversely, negative risk perceptions of adverse events following immunization also hinder vaccine uptake in last mile communities. Cunha and Dourado note that the timing and scale of mass vaccination campaigns can exacerbate negative risk perceptions among last mile communities. During such campaigns – which may aim to reach hundreds of thousands of people in a relatively short span of weeks or months – even rare adverse events may be perceived to be common occurrences.[120] Similarly, unforced medical errors can also undermine last mile communities' trust in vaccinators and diminish willingness to receive vaccinations. Cousins, for example, describe an incident wherein measles vaccines intended for a campaign in Syria were erroneously mixed with a muscle relaxant instead of diluent, leading to the deaths of 17 children and eroding public trust in vaccination.[121]

In the target population framing of the last mile, vaccine hesitancy, skepticism, or refusal – abetted by the growing threats of misinformation and disinformation – could also impede efforts to deliver vaccines to intended recipients, even as geographic, financial, or other systemic barriers to access are dismantled. Describing the difference between responding to outbreaks of endemic versus novel, emerging diseases, KI10 observed,

> "Endemic diseases have an aspect of trust in community perception. [The Expanded Programme on Immunization, EPI] is generally accepted as part of routine vaccination. For a new vaccination – such as in outbreaks – then trust and community acceptance are more difficult. Additionally, information availability regarding the vaccine is different for epidemics so people wonder what is new or different. The era of social media has also increased the issue of misinformation. Those are things we have to confront for epidemics but not so much EPI."

The literature corroborates these observations. False information about vaccine safety and perceived ulterior motives of health programs are powerful deterrents of both trust and vaccine uptake in LMICs during outbreaks, and often result in vaccine boycotts, bans, or other disruptive measures among last mile communities.[47,88] The literature frequently highlighted rumors that vaccines cause infertility as a major driver of vaccine hesitancy and refusal.[47,64,65,93,122] In many cases, too, a lack of awareness about vaccine availability and the benefits of vaccination among last mile populations further impedes vaccine uptake and confidence.[48,56,89,123]

2.4.7.4 Health Systems

In the health system last mile, low vaccine demand and suboptimal uptake may, in some cases, be symptoms of broader dissatisfaction with health system misalignment with community health priorities. Under-resourced, poor quality programs for delivering routine health services – coupled with weak community engagement and risk communication – could undercut vaccine demand during an emergency, particularly as epidemics wane and lingering cases are concentrated among last mile communities. This phenomenon has frequently been documented during polio eradication efforts in LMICs, wherein polio SIAs are poorly received among target populations unable to fulfill other, more highly prioritized needs such as access to food and essential medicines, basic checkups for children, and treatments for minor ailments.[59,61,70,93,124]

The failure of health systems to address community health priorities in an integrated fashion dovetails with vaccine forecasting and demand generation challenges once uptake reaches a saturation point during an outbreak. As KI1 shared,

> "We often talk about [forecasting challenges] with respect to access and sustainable supply, although it also applies to access to the last mile in terms of having an accurate sense of demand and feeding into the overarching forecast. For manufacturers, that's pretty critical. The more accurate the forecast is, the better we can supply volume at appropriate times and not waste volume. [And] there's a lot of demand generation work – making sure vaccines can actually get to the point of care that we're talking about."

On this point, Warigon et al. also suggest that targeted demand-side interventions – such as increasing media coverage of vaccination efforts, organizing health camps, and coupling vaccination with additional, community-prioritized health services – could help improve vaccine confidence among last mile communities.[60] Similarly, describing cholera control efforts across Africa, von Seidlein et al. write:

> "In every community, a small fraction of the population refuses to participate in mass campaigns, irrespective of the intervention. In Mozambique and Zanzibar, people residing outside the targeted areas travelled to vaccination centers, suggesting that, at the other end of spectrum, there is a population of highly motivated individuals who will actively seek to be vaccinated. The shape of the resulting response curve depends on the sensitization campaign preceding the vaccination campaign and on the perception of risk by the population. If the target population is adequately educated about the characteristics of the vaccine and each individual knows ≥1 person with cholera, a very high coverage is virtually assured."[66]

2.4.8 Population Immunity

The literature and key informant interviews revealed important challenges in building and sustaining population immunity during last mile vaccine delivery efforts.

Many such challenges manifest as second- or third-order effects of vaccine uptake, as immunization coverage gradually increases over the course of a mass vaccination campaign or program. Nevertheless, we have chosen to address population immunity challenges in this conceptual framework because they often modulate vaccine delivery, uptake, and effectiveness in last mile contexts.

2.4.8.1 Geography

The geographic last mile may present important population immunity challenges in the form of multiple or atypical reservoirs. The absence of non-human reservoirs for the smallpox virus, for example, was essential to the success of the global eradication program; however, Klepac et al. note that the presence of unknown or inaccessible animal or environmental reservoirs could complicate efforts to eliminate or eradicate a pathogen.[8] Haydon et al. define a reservoir as "as one or more epidemiologically connected populations or environments in which the pathogen can be permanently maintained and from which infection is transmitted to the defined target population. Populations in a reservoir may be the same or a different species as the target and may include vector species."[103] As such, identifying reservoirs becomes important once vaccinated members of a target population above critical community size can no longer maintain population immunity.[103] This requires close coordination and collaboration between human, environmental, and animal health workforces and surveillance systems.

The geographic last mile may also give rise to novel or atypical reservoirs that emerge as vaccination or other mitigation efforts progress, further jeopardizing population immunity. This phenomenon is illustrated by outbreaks of circulating vaccine-derived poliovirus, which are sparked by already-vaccinated individuals who continue to shed the virus.[125] On a related note, Lloyd-Smith postulates that pathogen eradication – and cessation of vaccination – creates a "vacated niche," whereby evolutionary mechanisms of competitive release could enable a different organism to occupy said niche or allow the eradicated pathogen to occupy the niche if re-introduced into the population.[126]

2.4.8.2 Epidemiology

Several documents also highlighted threats to population immunity as vaccination efforts progress toward the epidemiological last mile. Klepac et al., for instance, contend that extensive use of prophylactic measures like vaccines could generate selection pressures that result in pathogen adaptation or vaccine escape.[8] Kennedy and Read similarly note that when a given pathogen population consists of multiple serotypes, vaccination against a subset of serotypes could lead to an increase in prevalence of the remaining serotypes – a phenomenon that has been observed following vaccination against select strains of *Haemophilus influenzae*, *Streptococcus pneumoniae*, *Neisseria meningitidis*, and *Bordetella pertussis*.[127] In some cases, selection pressures could also give rise to vaccine escape. Describing the impact of conjugate polysaccharide vaccines on meningitis control, for example, Maiden defines vaccine escape as "the evolution or spread of variants that are not affected by vaccine-induced immunity, and are released from competition with those variants that are affected," noting that both phenomena may be driven by vaccination campaigns.[128]

Furthermore, as predominant pathogen strains decline due to vaccination, minor strains may become more common, as observed with wild poliovirus type 1 following eradication of types 2 and 3, as well as variola minor during the smallpox eradication program.

2.4.8.3 Target Populations

Suboptimal vaccine immunogenicity presents another challenge in the target population last mile, wherein low per-dose efficacy and strain interference among vaccine recipients could undermine delivery, uptake, and coverage. The inactivated poliovirus vaccine, for example – one of two vaccines used widely by GPEI – does not stimulate strong mucosal immunity in recipients, thereby enabling continued asymptomatic viral shedding and transmission among vaccine recipients.[129,130] Similarly, describing polio eradication efforts in 2011, Bhutta wrote that the widely used live attenuated oral poliovirus vaccine (OPV) induced “imperfect” mucosal immunity, even among children who had received as many as six or more doses.[84] Grassly, Nathanson, and Kew corroborate this finding, noting that large burdens of diarrheal disease in countries with endemic polio interfere with the vaccine’s ability to stimulate mucosal immunity, thereby blunting OPV effectiveness in endgame settings.[62,131] Additionally, Klepac et al. highlight the risk of waning immunity to certain vaccine-preventable infections like pertussis, which could lead to resurgent cases of disease – even in populations with ostensibly high vaccination coverage.[8] Finally, the doctrine of original antigenic sin – a term coined by Thomas Francis, Jr. to describe how the first infection encountered in life orients immune responses to subsequent infections – could also generate population immunity challenges in the target population last mile.[132] Because this phenomenon primes immunological memory to respond more robustly to original versus new antigens, sequential antigenic exposures could result in diminished vaccine effectiveness – a complication that has been documented in seasonal influenza vaccination efforts.[133]

2.4.8.4 Health Systems

Implementing effective dosing regimens presents another critical challenge to building population immunity in the health system last mile – one that is extremely specific to the disease and vaccine in question. Estívariz et al., for example, describe how shortening intervals between administering doses of monovalent or bivalent polio vaccine (from 4-6 weeks to 1-3 weeks) can more rapidly increase population immunity during outbreaks, particularly in settings experiencing conflict or insecurity.[134] However, in very young children, longer dosing intervals may be required to avoid interference from maternal antibodies. Estívariz et al. also acknowledge that fractional dosing (i.e., administering a fifth of a standard dose of polio vaccine) could enable campaigns to reach more children while reducing program costs and stretching manufacturing capacities in resource-constrained settings, but note that this approach may result in decreased vaccine immunogenicity.[134] Relatedly, a recent commentary by Wolff et al. (not coded as part of this literature review) articulates ethical considerations for administering fractional doses and altering intervals in a multi-dose regimen, such as the level of individual and community immunity to be achieved under an altered regimen compared to the manufacturer-recommended course of vaccination.[135]

2.4.9 Cross-Cutting Last Mile Challenges

The literature review and key informant reviews also revealed several broad considerations that cross-cut multiple last mile framings and thematic categories described above: funding, integration, and quality assurance. Here, we describe these considerations and their implications for vaccine delivery and uptake in last mile contexts.

2.4.9.1 Funding

Securing and sustaining enough funding to achieve desired levels of vaccination coverage during an epidemic – especially amid competing political and budgetary priorities – remains a perennial challenge across many LMICs. The literature described steep costs associated with manufacturing and purchasing vaccines, maintaining stockpiles, staffing vaccination programs, and monitoring target populations for incident cases of disease – which often grow as vaccine demand falls during the tail end of many epidemics.[131,136–139] Such fiscal challenges become particularly relevant during the epidemiological last mile of elimination and eradication programs, wherein the cost per case of disease prevented by vaccination typically escalates with increasing vaccination coverage and decreasing disease incidence.[8,140] The specific mechanism of vaccination also influences cost: Grabenstein et al., for example, report that vaccinating children through mass campaigns is costlier than via routine programs.[91]

Incentivizing donors and policymakers to continue subsidizing vaccination also grows harder if the cost-effectiveness of vaccination during late-stage disease control, elimination, or eradication efforts decreases relative to other mitigation and control measures.[6] Describing eradication programs –inherently costly endeavors for which sustaining financial support poses major challenges – Barrett et al. also acknowledge the concomitant opportunity costs and resource allocation dilemmas that donors, governments, and health programs must contend with: resources spent on eradication, for example, cannot be spent on other health programs and priorities, which raises questions about the practicality of funding eradication initiatives at the expense of strengthening health system capacities in resource-constrained settings. Citing Taylor, Barrett et al. further note that donors wield considerable influence over such spending decisions, which play out on enormous scales: for example, GPEI reported that roughly USD$5.1 billion would be required between 2019 and 2023 alone to implement its Polio Endgame Strategy.[82,141]

2.4.9.2 Integration

The issue of cost also intersects with health service integration considerations – particularly when last mile vaccination efforts fail to align with the priorities of a given target population. Recognizing that vaccination efforts during outbreaks are typically implemented in a vertical manner, several studies recommended using vertically channeled funds and resources to concomitantly strengthen post-outbreak systems and programs for routine immunization, noting that such an approach could help avert health system fragmentation and generate greater public demand for immunization services.[6,62,84,85,93] On this point, one key informant underscored the importance of meeting so-called "ancillary health obligations," asserting, "If you're going to do supplemental immunization activities, you need to collaborate with organizations addressing other issues like food insecurity or look into unconditional cash transfers to address economic issues. It's not just smart strategically, but also smart ethically to meet the needs of people where they're at and they're not just a means to get to 'X' vaccination target." Similarly, another KI4 summarized these considerations thus:

> "It really comes down to cost, how it's so expensive to reach just a few people, and how those funds could be used to benefit more people or for something else. Until there's no disease anywhere or we have enough coverage for herd immunity, then the more worrying aspect is this reproduction of injustice where we already have an underserved population [that] doesn't have access to basic health infrastructure – or even health information in many cases – [that is] neglected by the government, health agencies, and everyone, and the justification to not go is just that they're not important enough. Instead of making the investment for infrastructure, supplementary immunization activities, or even engagement, you're opening up the door for more mistrust when you do get there."

KI4 also added, "We've all seen the flaws of highly siloed vertical programs. We want to integrate them into health systems and not create disease exceptionalism…There is a sense of concentrating on one disease to the detriment of addressing other health concerns." In turn, chronic failures to address community health needs have a cumulative effect of eroding trust in vaccination programs, leading to resentment and unwillingness to get vaccinated – a phenomenon that has been observed in when repeated rounds of polio SIAs are conducted in settings with limited access to other health services.[59] Nevertheless, integrating vaccination into broader systems of health and social service provision remains an elusive goal in practice. Andrus et al., for example, highlight several challenges in linking outbreak response assets to longer-term health systems-strengthening initiatives, including ensuring sufficient epidemiological and laboratory surveillance capacities, building human resource workforces, sustaining public demand for vaccination and other integrated services, and garnering long-term political support for such efforts.[88]

2.4.9.3 Quality Assurance

Quality assurance also emerged from the literature as an important cross-cutting last mile consideration in the context of surveillance, data collection, health workforce management, surveillance, and planning. WHO has cited poor SIA campaign quality as a barrier to reaching every child in need of a polio vaccination.[142–145] The quality of surveillance also varies considerably across resource-constrained settings. Orenstein et al, for example, note that while case-based surveillance systems for measles exist in 188 countries, 45% of those countries fail to report case-based data to the World Health Organization (WHO), and reported data on vaccination status is frequently incomplete. As a result, many measles burden estimates rely heavily on mathematical modeling versus empirical data, and public health responders often have limited evidence with which to inform vaccination strategies.[68] Understaffing and poorly trained workforces were also cited as factors contributing to low surveillance system sensitivity, poor data quality, and suboptimal reporting.

Additionally, Grabenstein et al. underscore how recurrent medical errors, such as administering the wrong product or using an incorrect diluent, could create program setbacks.[91] Kew et al. further caution that gains made by immunization programs in last mile settings are fragile and prone to setbacks if such programs fail to maintain the quality of services provided.[49] Describing polio elimination efforts in northern Nigeria, for example, Roberts reports that lapses in program quality (e.g., absentee vaccinators and failure to pay staff) resulted in the program missing over half of children targeted for immunization; this, in turn, eroded public confidence in polio vaccination.[146] Notably, in recent years, the Government of Pakistan has prioritized several measures to improve the quality of ongoing polio immunization campaign quality: intensifying microplanning activities, ensuring timely payments to program staff, strengthening intra-campaign supervisory and accountability mechanisms, improving pre- and intra-campaign data collection, and encouraging implementation of Lot Quality Assurance Sampling surveys during campaigns.[82,95,147]

2.5 DISCUSSION

The scoping literature review and key informant interviews described herein framed the last mile of vaccine delivery during infectious disease outbreaks in LMICs in terms of geography, epidemiology, target populations, and health system performance; identified and described associated challenges within each framing; and informed development of a conceptual framework for considering said challenges in global public health practice. The literature and interviews highlighted numerous intersections between many last mile challenges in vaccine delivery and uptake, underscoring how convergence between multiple dimensions of the last mile across various axes of vulnerability give rise to last mile complexities that demand targeted public health solutions.

The conceptual framework produced in this investigation could support analyses of last mile challenges across a broad range of LMIC and resource-constrained settings. These challenges raise distinctive obstacles to outbreak response efforts in such settings and should be accounted for more explicitly during routine outbreak planning efforts. Donors, for example, could use the framework to inform funding decisions around ongoing mitigation, elimination, or eradication initiatives. The framework could also support public health officials in LMICs in planning more systematically for contingencies in late-stage disease control efforts, especially if those countries choose to transition away from donor-driven models of immunization to more integrated systems of holistic care. The structure of the framework – which disaggregates last mile challenges across four framings and six thematic categories – could also help end users identify opportunities for cross-sector collaboration between relevant stakeholders. Though the framework does not attempt to prioritize, rank, or weight last mile challenges, it does provide cross-sector stakeholders with a shared mental model for conceptualizing, organizing, and discussing these challenges. Forging cross-sector connections, in turn, could support downstream efforts to integrate vertical vaccination capacities into routine systems of care.

Because the literature search was conducted in May 2020, this scoping review does not reflect a considerable body of scholarship examining challenges associated with COVID-19 vaccine delivery. However, many of the last mile challenges described herein have already manifested in high-income settings where COVID-19 vaccine rollout efforts are well underway. At the time of this writing, for example, many parts of the United States report critical challenges as national vaccination efforts progress: in the epidemiological last mile, detecting viral variants and monitoring vaccinated individuals for breakthrough cases of COVID-19; in the geographic last mile, delivering vaccines to rural settings lacking adequate freezer capacity; in the target population last mile, increasing uptake among Black, Latinx, Pasifika, and Indigenous populations; and finally, in the health system last mile, generating vaccine demand among resistant groups through targeted incentives.[148–151] Similar and other last mile challenges are also likely to emerge in LMICs as vaccine distribution and delivery efforts scale up across the Global South, which will undoubtedly inform future analyses of this topic and support refinement and validation of the conceptual framework. Even outside the context of COVID-19, a systematic approach to considering last mile challenges may also prove useful in the near term, given how the pandemic has disrupted routine immunization activities worldwide, thereby increasing the likelihood of vaccine-preventable outbreaks among susceptible populations.[152]

Though the scoping review and key informant interviews covered considerable ground, this investigation does have some limitations. First, the demographic breakdown of the coded literature revealed some methodological gaps in previous analyses of last mile challenges. Most descriptions of these challenges originated largely from review articles and policy statements presenting mostly anecdotal evidence; few documents, if any, attempted to define or analyze the last mile using quantitative approaches or via robust experimental designs (see Figure 3). Further analysis of the coded literature also demonstrates that the overwhelming majority of published research on last mile challenges addressed the ongoing global effort to eradicate polio, with particular focus on Pakistan and Nigeria; significantly fewer documents examined other diseases or countries (see Tables 1 and 2). As a result, some findings from this investigation may disproportionately reflect challenges that are specific to polio immunization efforts in a relatively narrow pool of countries.

Second, though last mile challenges are context-specific, this scoping review was setting-agnostic; that is, it did not focus on a single country, district, province, or other confined geographic unit. Thus, it is likely that the resultant framework does not capture all the idiosyncrasies of a given health system environment. These limitations underscore a need for further characterization of last mile challenges in vaccine delivery across more diverse settings, in the context of a broader range of vaccine-preventable diseases, and via systematically applied methodological approaches.

Further research applying different methods is also needed to elucidate the causal mechanisms or pathways underpinning last mile challenges, as well as any cause-and-effect relationships between them. Future analyses may benefit from applying a complex adaptive systems lens to last mile challenges to identify underlying causal pathways, feedback loops, tipping points, and other phenomena that may give rise to said challenges.[153] There were also several issues that did not figure prominently in our literature review and interviews, but certainly warrant further explication in last mile contexts, such as the power dynamics underpinning donor-recipient relations, ethical considerations, and strategies for promoting health equity. By focusing on specific settings or contexts, future analyses might also be able to articulate more concrete boundaries for the last mile itself. Finally, because many last mile challenges are particular to specific settings, it did not make sense for this investigation to attempt an *a priori* weighting of the importance of some last-mile challenges relative to others (e.g., whether cold chain deficiencies are more urgent challenges than weak risk communication). However, applying the Delphi method or nominal group techniques in future studies could help public health decision-makers in a given setting prioritize the most pressing or relevant challenges.[154,155]

2.6 CONCLUSION

Last mile challenges in vaccine delivery during outbreaks raise distinctive obstacles to protecting population health in low- and middle-income settings across the world. These challenges often converge in complex ways, impeding vaccine delivery, uptake, and high immunization coverage. Constructing a typology that accounts for a broad gamut of challenges likely to be encountered during last mile vaccination efforts in LMICs is a step toward a more systematic accounting of these considerations in routine preparedness activities.

This investigation drew from peer-reviewed literature, grey literature, and semi-structured key informant interviews to develop such a typology. The framework presented herein – which conceptualizes the last mile in terms of geography, epidemiology, target populations, and health system performance – offers one approach to holistically considering last mile challenges. Examining these challenges across the domains of governance and leadership, surveillance, workforce, program implementation, vaccine uptake, and population immunity could aid public health decision-makers in forecasting relevant challenges at different stages of outbreak response. The framework could also support efforts to develop targeted solutions to said challenges in specific contexts, and across a broad spectrum of vaccine-preventable diseases. Future studies of this topic may benefit from incorporating lessons learned during the ongoing COVID-19 pandemic, as well as from deploying different methods to characterize the relationships between different last mile challenges.

The inherently vertical (i.e., disease-specific) nature of outbreak vaccination efforts further underscores the importance of resolving last mile challenges. By addressing these challenges in emergency contexts, public health practitioners may glean insights and develop best practices for improving routine health service delivery for both communicable and non-communicable diseases. Perhaps most importantly, by strengthening capacities to deliver vaccines to hard-to-reach populations – which are often geographically isolated, socioeconomically marginalized, and face structural barriers to vaccine access – public health leaders and practitioners can take important steps toward dismantling health system inequities. Ultimately, more focused consideration of these challenges promises to shorten the last mile toward desired population health outcomes.

AIM TWO

Post-Epidemic Health System Recovery: A Comparative Case Study Analysis of Routine Immunization Programs in the Republics of Haiti and Liberia

> "Historically, pandemics have forced humans to break with the past and imagine their world anew. This one is no different. It is a portal, a gateway between one world and the next. We can choose to walk through it, dragging the carcasses of our prejudice and hatred, our avarice, our data banks and dead ideas, our dead rivers and smoky skies behind us. Or we can walk through lightly, with little luggage, ready to imagine another world. And ready to fight for it."

Arundhati Roy

“The Pandemic Is a Portal”

3.1 ABSTRACT

Acute infectious disease epidemics in resource-constrained settings often disrupt delivery of core health services, such as routine immunization. Rebuilding and strengthening routine immunization programs following major epidemics is an essential step toward improving equitable vaccination coverage in such settings. Here, we present findings from a comparative case study analysis examining post-epidemic routine immunization program recovery in the Republics of Liberia and Haiti following the 2014-16 West Africa Ebola epidemic and the 2010s cholera epidemic, respectively. After triangulating data between the peer-reviewed and grey literature, key informant

interviews, and quantitative databases, we apply the Essential Public Health Services framework to facilitate cross-case comparison and identify relevant barriers and facilitators of immunization program recovery. We find that embedding in-country expertise within outbreak response structures, respecting governmental autonomy and self-determination, aligning post-epidemic recovery plans and policies, and integrating outbreak response assets into robust systems of primary care contribute to higher, more equitable levels of routine immunization coverage.

3.2 INTRODUCTION

Acute infectious disease outbreaks are major causes of morbidity and mortality worldwide. Such crises place enormous strains on health systems to both scale up core public health activities to mitigate the threat at hand and absorb escalating demand for emergency medical services. Concurrently, outbreaks also derail routine health service delivery by diverting needed human, financial, and medical resources away from essential health programs. The ongoing COVID-19 pandemic, for example, has disrupted cancer care across the globe by delaying stem cell shipments, causing drug shortages, and halting surgeries.[156] In some cases, protective measures like travel restrictions, curfews, and physical distancing have impeded patients from seeking care altogether.[157] In another example, the U.S. Centers for Disease Control & Prevention (CDC) reports that coverage of routine and adolescent vaccinations in some U.S. jurisdictions decreased significantly during the first six months of the pandemic.[158] Such dysfunction is especially consequential in resource-constrained settings with large baseline burdens of endemic disease, where barriers to accessing basic health services are routinely high, and where even routine care-seeking could result in catastrophic health spending.

Though the disruptive impacts of major outbreaks on health system performance are well-characterized, the mechanics of *post*-epidemic health system recovery remain somewhat obscure.[159–161] Emergency planning efforts often prioritize acute response activities (e.g., managing patient surges, reducing disease incidence and mortality) over longer-term health system considerations and population health needs, such as resuming delivery of routine immunization, nutrition, mental health, and reproductive health services.[162] A recent analysis of 154 COVID-19 response plans from 106 countries, for instance, reveals that only 47% included provisions for maintaining essential health services, while only 7% addressed monitoring and evaluation of such services.[163] Recouping losses of health service coverage, rebuilding trust among target populations, and rectifying distortions of national health priorities due to external donor influence are further examples of post-epidemic health system recovery challenges.[164] Underpinning many of these challenges is an imperative for decision-makers to integrate vertically channeled resources for outbreak response into resilient systems for providing routine care.

Routine immunization considerations are particularly important during post-epidemic recovery. Immunization is among the most effective public health interventions, and high levels of coverage are both key to averting outbreaks of vaccine-preventable diseases and an important proxy of strong health system functioning.[59,165] Two recent crises, the 2014-16 West Africa Ebola epidemic in Liberia and the 2010s cholera epidemic in Haiti, serve as instructive – and contrasting – cases of routine immunization program recovery after destabilizing outbreaks. Though national coverage of the first dose of measles-containing vaccine (MCV1) plummeted to 58% in Liberia in 2014 (the first year of its Ebola epidemic), this estimate surged to 87% in 2017, the year after the epidemic was declared over. Similarly, the percentage of Liberian districts reporting over 80% MCV1 coverage increased from 7% in 2014 to 80% in 2018. By contrast, national MCV1 coverage in Haiti stagnated between 64-69% during its years-long cholera epidemic (2010-2019), while the proportion of districts with MCV1 coverage above 80% fell well below 50% during this period.[166]

This paper examines the factors that contributed to these differing trajectories, both historical and those related to public health practice during and after each country's epidemic. By comparing and contrasting the post-epidemic measures implemented in each setting, we identify facilitators and barriers of efforts to rebuild and strengthen routine immunization programs.

3.3 METHODS

We performed a case study analysis to explore efforts to integrate outbreak response assets into routine immunization programs in LMICs and improve post-epidemic routine immunization coverage. We utilized a comparative, "most-similar" design, wherein we examined two distinct cases that are similar across relevant background conditions but differ across select independent variables and the outcome of interest.[167] Such comparative approaches have been applied in both public health and political science research to suggest potential associations between variables and outcomes of interest.[168,169]

As it did not qualify as human subjects research, this investigation was deemed exempt from full review by the Institutional Review Board at the Johns Hopkins Bloomberg School of Public Health (FWA #00000287).

3.3.1 Case Selection

The two cases chosen for this analysis were the 2014-16 West Africa Ebola epidemic in Liberia and the 2010s cholera epidemic in Haiti. These cases were selected by reviewing WHO's Disease Outbreak News archive of notifiable events reported by country and year (reviewed in October 2019).[170] To ensure availability of relevant, recently published literature and data, we sought high-profile, rapid onset, naturally occurring infectious disease epidemics that took place in LMICs, resulted in considerable morbidity and mortality, overwhelmed the health system capacities of affected countries, demonstrated potential for transnational spread, and required significant international intervention and coordination to mitigate. Outbreaks that occurred before 2010 were excluded for the same reasons. Influenza outbreaks were excluded since the disease generally poses a seasonal (versus acute) threat. Polio outbreaks were also excluded from consideration, given longstanding international commitments toward eradication and relatively small numbers of reported cases per outbreak. Major outbreaks meeting the aforementioned criteria include: the 2010s Haiti cholera epidemic, the 2012 outbreaks of meningococcal disease across the African Meningitis Belt,[†] the 2014-16 West Africa Ebola epidemic (which caused widespread

---

[†] The so-called "African Meningitis Belt" refers to the region of sub-Saharan Africa stretching between Senegal and Ethiopia that reports the world's largest burden of meningococcal meningitis (approximately 30,000 cases per year) (Africa Centers for Disease Control & Prevention).

transmission across Guinea, Liberia, and Sierra Leone), the Zika epidemic of 2015-16 (which affected many countries worldwide), a 2015 typhoid fever outbreak in Uganda, a 2015 cholera outbreak in Iraq, a 2015 outbreak of meningococcal disease in Nigeria, and the 2018-2020 Kivu Ebola epidemic.[170]

From this list, we determined that the 2014-16 Ebola epidemic in Liberia and the 2010s cholera epidemic in Haiti were the most comparable cases. The World Bank classifies Liberia and Haiti as low-income countries with gross national incomes of less than $1,025 per capita.[171] Both are small countries that share similar governance structures: they are representative, democratic, presidential republics with bicameral legislatures.[172,173] The national health systems of both countries also share a similar structure, being comprised of primary-level clinics, service delivery points, and community-based health centers offering basic preventive and curative services; secondary-level hospitals providing emergency, diagnostic, and surgical services; and tertiary-level facilities providing specialized surgical services and advanced care for non-communicable conditions.[174,175] Furthermore, the Ebola and cholera epidemics were both preceded by major destabilizing events that drastically weakened health system capacities: in Haiti, a catastrophic earthquake, and in Liberia, the First and Second Liberian Civil Wars. Both countries also rely heavily on foreign aid and external donors to subsidize basic health service provision.[176,177] Yet, as previously discussed, WHO and UNICEF report contrasting trends in post-epidemic routine immunization coverage between the two countries – a feature of these cases that enables theoretical replication.[178]

Our chosen unit of analysis in each case was the post-epidemic process of immunization program recovery at the national level, whereby resources channeled vertically toward outbreak response efforts were successfully leveraged (or not) to increase routine immunization coverage.

3.3.2 Data Collection

To ensure the rigor of our analysis, we applied trustworthiness criteria originally articulated by Lincoln and Guba and elaborated upon by Nowell et al.: credibility, dependability, transferability, and confirmability.[179] Data were gathered from and triangulated between three sources to ensure credibility: 1) peer-reviewed and grey English-language literature; 2) publicly available quantitative databases; and 3) key informant interviews with subject matter experts.

First, we performed a rapid review of the peer-reviewed, English-language literature in PubMed and Scopus, identifying scholarly analyses of routine immunization challenges in Liberia and Haiti both during and after the Ebola and cholera epidemics, respectively. Rapid reviews – also known as rapid evidence assessments – involve a critical appraisal of what is already known about the topic of interest, with the goal of informing decision-making in a timely, efficient manner.[180,181] Such assessments typically seek to examine the impact of a given variable or intervention, or the antecedents of a given outcome, which suited the purpose of this case study analysis.[182] The results of our rapid review were narrowed to papers published between the ten years prior to each country's epidemic and the present day, and the following search terms were used:

- “Liberia” AND “routine immunization” OR “immunization” OR “vaccination”
- “Haiti” AND “routine immunization” OR “immunization” OR “vaccination”

We also purposively scanned the grey literature to identify technical reports, whitepapers, and other relevant documents relating to post-epidemic routine immunization funding, programs, and activities in both countries. These documents and their sources include:

- Joint Appraisal Reports (Gavi, the Vaccine Alliance, “Gavi”)
- Comprehensive Multi-Year Plans for Immunization (Gavi)
- Foreign aid records (U.S. Agency for International Development, “USAID”)
- UN Digital Library (United Nations, UN)
- Multi-Partner Trust Fund Office Gateway (United Nations)
- Development Experience Clearinghouse (USAID)
- Joint External Evaluations (WHO)
- Post-Disaster Needs Assessments (UN Development Programme)
- National Action Plans for Health Security (WHO)
- ReliefWeb search results

We also used forward- and backward-snowballing methods (i.e., electronic citation tracking and parsing the references of initially identified sources, respectively) to identify additional relevant documents.

Next, we obtained quantitative data describing vaccination coverage, immunization and other health system capacities, health spending, and humanitarian and foreign aid disbursements in both countries. Due to missing or incomplete data in the ten-year window preceding each epidemic, and to ensure that our analysis captured the immediate health system impacts following each epidemic, we chose to focus on data from the five-year period preceding and following the year in which each country's epidemic began. These data and their corresponding sources are presented below.

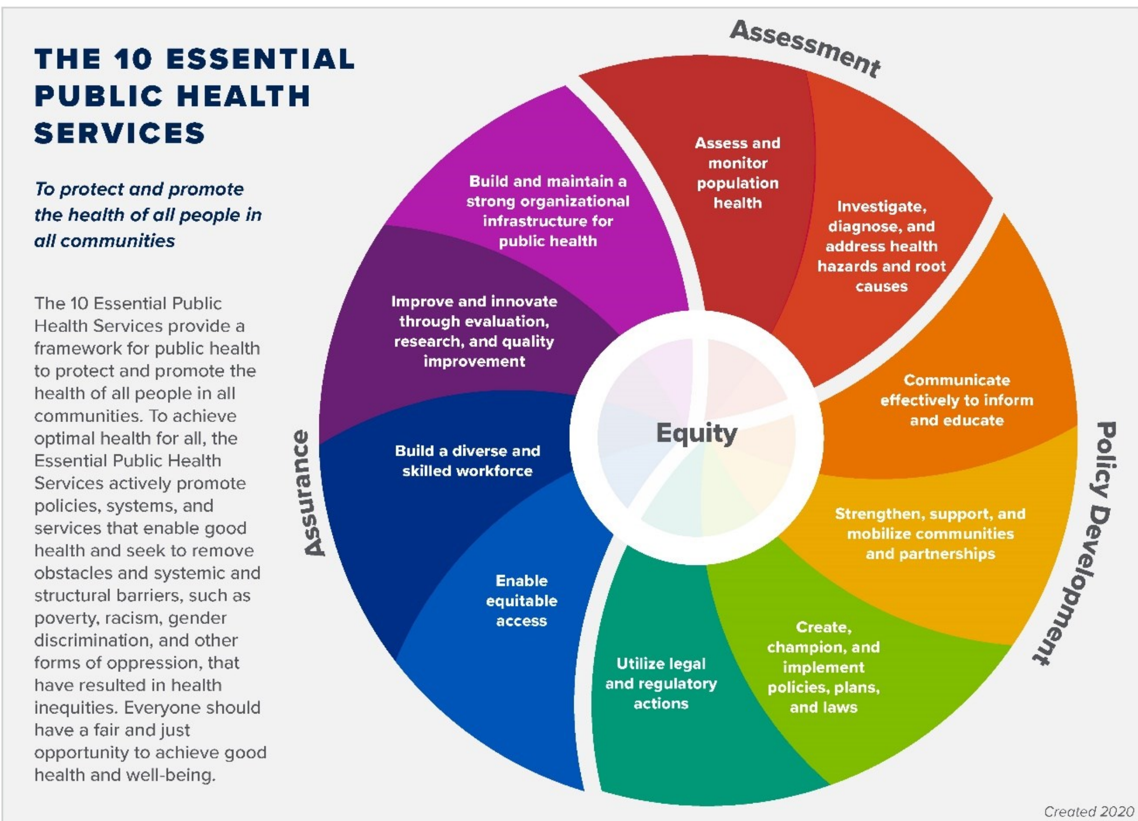
- **WHO-UNICEF Joint Reporting Forms**
  - Percentage of districts with microplans to raise immunization coverage
    Percentage of districts with MCV1 coverage ≥ 80%
  - Percentage of districts with coverage of the third dose of diphtheria-tetanus-pertussis-containing vaccine (DTP3) ≥ 80%
  - Drop-out rate between the first dose of diphtheria-tetanus-pertussis-containing vaccine (DTP1) and MCV1
- **WHO Global Health Expenditure Database**
  - Domestic general government health expenditure per capita
  - External health expenditure per capita
- **ForeignAssistance.gov (USAID)**
  - Health sector assistance
  - Humanitarian sector assistance

The third arm of data collection involved semi-structured interviews with key informants who currently work or had formerly worked in the health or humanitarian response sectors in either Liberia or Haiti during or after each country's respective epidemic, and who had relevant subject matter expertise in routine immunization, infectious disease epidemiology, outbreak response, health systems-strengthening, community health and primary care, policy, or governance. Drawing from the literature review, *a priori* knowledge, and the Essential Public Health Services framework (see "Data Analysis" below), we developed a preliminary interview protocol to help guide discussions with key informants (see Appendix B). Next, we identified interviewees from the peer-reviewed and grey literature, from the investigators' existing professional networks, and via snowballing (i.e., soliciting recommendations from confirmed interviewees). We sent interview invitations to 82 individuals; ultimately, a total of 21 individuals agreed to participate, including 10 with expertise on Haiti and 11 experts on Liberia. A descriptive, de-identified roster of confirmed key informants is provided in Appendix C. The interviews took place between June 7-August 5, 2021, ranged between 45 minutes to an hour each, and were conducted in English. One member of the project team (Ravi) led all the interviews, which were held and recorded via video conference or phone. Interviews proceeded on a not-for-attribution basis to encourage frank conversation, and participants provided oral consent prior to recording. A second team member took detailed notes on each call, and all recordings and notes were archived on a password-protected server accessible only to the project team. We ceased soliciting additional informants once no significant or novel findings emerged from subsequent interviews.

3.3.3 Data Analysis

We first performed an informal literature search to identify potential analytical frameworks with which to perform cross-case comparisons. While we discovered numerous frameworks for conceptualizing health system resilience, risk reduction, and community recovery from natural disasters, we were unable to identify any that were specific to long-term health system recovery following infectious disease crises. However, the revised Essential Public Health Services framework ("the Framework") emerged as a possible cross-case comparative tool (see Figure 5).[183]

Figure 5. The Essential Public Health Services Framework



The Framework was originally developed in 1994 and articulates the core functions that public health systems should be able to perform.[184] Furthermore, there are precedents in the literature for conceptualizing and studying recovery from public health crises using this Framework. Fitter et al., for example, have applied the framework to examine post-earthquake and -cholera health system recovery in Haiti, while others have described it as a roadmap for post-disaster community revitalization.[185–187] In September 2020, the Public Health National Center for Innovations and the deBeaumont Foundation convened a group of stakeholders to revise the Framework to more explicitly center health equity considerations.[188] As such, we felt that the revised Framework would be a suitable tool for comparing post-epidemic immunization program recovery in Liberia and Haiti.

We coded the literature and interview notes in NVivo 12, using the components of the Framework as our coding scheme; this approach also helped us to organize the data and perform cross-case analyses.[189] During the coding process, we iteratively identified new themes that were not articulated in the original Framework. In the cross-case analysis, we used the Framework as a matrix to order data abstracted from each case and examine similarities and differences between cases across the thematic codes – a technique described by Miles, Huberman, and Saldaña as "stacking comparable cases" – and describe additional emergent themes.[190] By critically reviewing the completed matrix for similarities and differences between the two cases, we identified factors that facilitated or impeded equitable vaccination coverage in post-epidemic Liberia and Haiti. As part of the cross-case analysis, we also present descriptive statistics for each of the aforementioned quantitative measures in Table 3, in addition to incorporating them throughout each case narrative to illustrate trends in pre- and post-epidemic health system functioning in each country. We also used Stata 17 to perform one-way repeated measures analyses of variance (ANOVA) to assess the potential significance of changes in these measures during the five years preceding and following the year of epidemic onset in each country.[191]

Finally, to ensure the transferability of our findings, we constructed thick descriptive narratives for each case, incorporating findings from the literature, interviews, and quantitative databases.[179] Mills, Durepos, and Wiebe write that “case narratives are sensory representations derived from oral, document, or observational sources” that support model- or theory-building, noting that thematic analysis is also a valid approach to narrative development.[192] Coding the literature and interview content with the Framework (as described above) helped us prioritize information to include in each narrative, and relevant quotes from informants were verified by reviewing interview recordings.

3.3.4 Reflexivity Statement

The research team consisted of a lead investigator (Ravi, a native English speaker) and a junior investigator (a native English speaker with intermediate reading proficiency in French). Both investigators are U.S. citizens holding graduate degrees in public health, and at the time of this writing, were employed as faculty at a large research university in the United States, where they study a broad range of public health preparedness and global health security-related issues. Ravi (also a graduate student) conceptualized the analysis, developed the interview protocol, led the interviews, was the primary data analyst, and drafted this manuscript. Both investigators participated in data collection and regularly held peer debriefings to further strengthen the dependability and credibility of this investigation.[179] Due to the COVID-19 pandemic, Ravi was unable to travel to Haiti or Liberia, and acknowledges that her professional background and lack of firsthand familiarity with these countries have shaped this analysis.

3.4 FINDINGS

Below, we present descriptive case narratives of post-epidemic routine immunization program recovery efforts for each case, drawing on data collected from the key informant interviews, databases, and published literature. The case narratives begin with brief discussions of key historical events in Haiti and Liberia. These historical summaries were developed largely independently of the data collection and analytical approaches described in the methods section, which focused explicitly on gathering data pertaining to immunization program recovery. Rather, these summaries are meant to provide relevant contextual details and inform broader understandings of health system functioning in Liberia and Haiti. Throughout each case narrative, we refer to key informants by anonymized alphanumeric identifiers (see Appendix C).

3.4.1 Haiti

3.4.1.1 Historical Overview

The recent trajectory of Haiti's routine immunization efforts is as much a consequence of the country's tumultuous history as they are shaped by the 2010 earthquake and the 2010s cholera epidemic. In 1791, an insurrection led by Toussaint Louverture and other enslaved Haitians sparked a long and bloody revolution against France – the largest slave-led revolt since Spartacus' rebellion against the Roman Empire nearly 2,000 years prior.[193] Haiti emerged victorious in 1804 as the first Caribbean nation to liberate itself from its colonizer, but the aftermath of the revolution plunged the country back into centuries-long turmoil. The French monarch, Charles X, deployed armed forces to Haiti, forcibly demanding 150 million francs from the new nation to indemnify its former colonizers against lost revenues from slavery. This act of extortion mired Haiti in debt, decimated its economy, and erased its political autonomy in all but name. Haiti finally serviced its full debt to France in 1947, by which time it had paid back more than twice the original sum owed: the modern equivalent of over USD$20 billion.[194,195]

The United States' interference in Haitian affairs further set the stage for the country's present-day health system woes. In the late 1800s, the U.S. grew increasingly interested in annexing Haiti to "secure a defensive and economic stake in the West Indies" – a strategy that came to fruition in 1915, when a mob murdered Haiti's then-President Vibrun Guillaume Sam in Port-au-Prince.[196] The U.S. – another of Haiti's major creditors, in addition to France – quickly seized control of the National Bank of Haiti and unilaterally transferred millions of dollars' worth of gold to the National City Bank of New York, claiming it as partial repayment of Haiti's debts.[197] President Woodrow Wilson then ordered the U.S. Marines to occupy Port-au-Prince on grounds of protecting U.S. foreign interests.[196] The Haitian-American Convention,[‡] ratified in

[‡] Article XIII of the Haitian American Convention states: "The Republic of Haiti, being desirous to further the development of its natural resources, agrees to undertake and execute such measures as in the

September 1915, subsequently granted the U.S. authority to control Haiti's public finances for the next ten years and appoint a sanitation engineer to oversee public health and development activities.[198] "To Belgium's Congo, to Germany's Belgium, to England's India and Egypt, the United States has added a perfect miniature in Haiti," wrote the American journalist Herbert J. Seligmann in 1920.[199]

The American occupation of Haiti – a violent, militarized enterprise masquerading as a benevolent humanitarian mission – lasted until 1934, during which time the U.S. Navy and Marines ineptly attempted to modernize Haiti's public health and sanitation infrastructure.[200] The military's initial efforts to study tropical diseases, construct sanitation systems, build hospitals, and provide medical care garnered minimal institutional and financial support from the U.S. government, and did little to improve living conditions for the vast majority of Haitians.[200] In light of these failures, the U.S. solicited the Rockefeller Foundation to conduct a major health survey of Haiti. The survey met with considerable resistance from the Haitian people and established precedents for enlisting nonstate actors as instruments of state interests and claiming the mantle of development as pretext for continued occupation.[201] The so-called process of "Haitianization" eventually began in 1931, whereby the U.S. gradually relinquished control of the country's public institutions to the Haitian government – but in doing so, sabotaged the country's fledgling health system. By order of the U.S.-appointed Sanitation Engineer, health budgets were slashed, leaving patients to pay for medicines and health supplies out-of-pocket.[200]

---

opinion of the high contracting parties may be necessary for the sanitation and public improvement of the Republic under the supervision and direction of an engineer or engineers, to be appointed by the President of Haiti upon nomination by the President of the United States, and authorized for that purpose by the Government of Haiti."

Over time, the deliberate, methodical efforts of state and nonstate actors to atrophy Haiti's public sector capacities have led the country to be dubbed "a republic of NGOs."[202] In 2011, for example, as much as 99% of all aid earmarked for Haiti went to the estimated 10,000 active humanitarian agencies, contractors, and other nonstate service providers operating in-country, with a mere 1% channeled toward the national government or other public institutions.[203] Connecting the legacy of Haiti's colonization to the current state of its routine immunization efforts, KI1 shared:

> "Haiti is the first independent country [in the Caribbean] and they're very proud of that. You have to respect that and navigate the hate-love relationship with the international community. That's the cultural. The political is linked to that. It's the whole dynamic of the U.S. on one side and [the Pan-American Health Organization, PAHO] on the other side, and the different NGOs that are present…It's not the core business of public health people that want to maintain a 95% immunization rate. That's not the political agenda behind routine immunization or a campaign, [but] you end up in a political arena that is dealing with issues that have nothing to do with public health. That is, as I've seen, the core issue with immunization."

PAHO affirms these observations about Haiti's singular historical trajectory, writing, "Although it is making a consistent effort to join regional institutions, few if any other members share the same challenges or background, or even understand its culture. Haiti is not fully integrated as an equal member in the Caribbean or Latin America. It is an orphan without siblings, but with many foster parents."[204]

Following a 2004 coup wherein former President Jean-Bertrand Aristide was ousted from power, the United Nations issued a resolution to establish the Mission des Nations Unies pour la stabilisation en Haïti (MINUSTAH).[205,206] MINUSTAH was a peacekeeping mission comprised of militarized forces mandated to restore the rule of law and strengthen public institutions – a measure that echoes Haiti's long history of subjugation by external powers and annexation of its state functions. In 2009, the year before its earthquake, Haiti was ranked among the most corrupt countries in the world.[207] Its weakened public sector meant that critical services (i.e., sanitation, healthcare, education, military, and fire safety) were either nonexistent or outsourced to private and civil society actors, and only a small police force comprised its disaster response workforce.[208]

3.4.1.2 The 2010 Earthquake: Impacts and Response

A catastrophic, 7.2 magnitude earthquake struck Haiti on the afternoon of January 12, 2010, affecting some 3 million people across the country and leaving one million persons homeless; the official death toll has been disputed, with some estimates placing the number of deaths at 158,000, while the Haitian government reports as many as 316,000 lives lost.[209,210] The earthquake also destroyed an estimated 250,000 homes and 30,000 businesses, sparking protests over the initially sluggish influx of emergency assistance.[211]

A Post-Disaster Needs Assessment (PDNA) – requested by interim Prime Minister Dr. Ariel Henry and performed by the United Nations Development Programme – highlighted the earthquake's devastating impacts on the country's health system. Within the immediate disaster zone, 39 of 40 hospitals were damaged or destroyed, along with the Ministry of Public Health and Population's (Ministère de la Santé Publique et de la Population, MSPP) main building and the United Nations headquarters.[208] The total costs associated with health sector damage and disruption were estimated at roughly USD$274 million.[212] The earthquake also prompted an exodus of nearly 600,000 people from the earthquake's epicenter near Port-au-Prince to neighboring towns and cities, straining health systems in host jurisdictions.[212]

Perhaps most alarmingly, the earthquake's aftermath threatened the already tenuous state of population health in Haiti. Prior to the earthquake, stark inequities were reported in health service access and utilization, reflecting the impact of historical and political chaos on its health system. Maternal and infant mortality rates were reported at 630 deaths and 57 deaths per 100,000, respectively; only 6% of the poorest women in Haiti gave birth in a health facility, compared to 65% of the wealthiest; and 47% of the population lacked access to healthcare altogether.[212] In 2013, a few years after the earthquake, only 43% (n=332) of Haiti's 786 primary health facilities were deemed to be accessible, while a mere 4% (n=30) and 6% (n=42) reported effective service delivery and satisfactory primary care functions, respectively.[213] Furthermore, with a health workforce density of 0.65 doctors, midwives, and nurses per 1,000 people in 2015, Haiti

– a country of over 10 million people – falls well below the WHO-recommended minimum health workforce density (4.45 doctors, midwives, and nurses per 1,000) required to achieve the Sustainable Development Goals.[214]

Between 2003 and 2009, out-of-pocket costs ranged between 39-48% of the country's total health expenditures while domestic government fluctuated between 6-21% -- a consequence of Haiti's fee-for-service healthcare scheme.[215] In fact, Haiti's Expanded Programme on Immunization (EPI) estimated that a basic package of health services, including immunization, would cost roughly USD$60 per capita, well above the government's then-health expenditures of USD$31 per capita.[216] Immunization coverage during this period was also dangerously low: Haiti's 2005-06 Demographic Health Survey (DHS) reported that a mere 25.7% of children in the wealthiest quintile had received all age appropriate vaccinations, compared to only 9.1% of their poorest counterparts.[217] Figures 6, 8, and 9 (next page) illustrate trends in immunization coverage and under-5 mortality in Haiti during its pre- and post-earthquake periods.

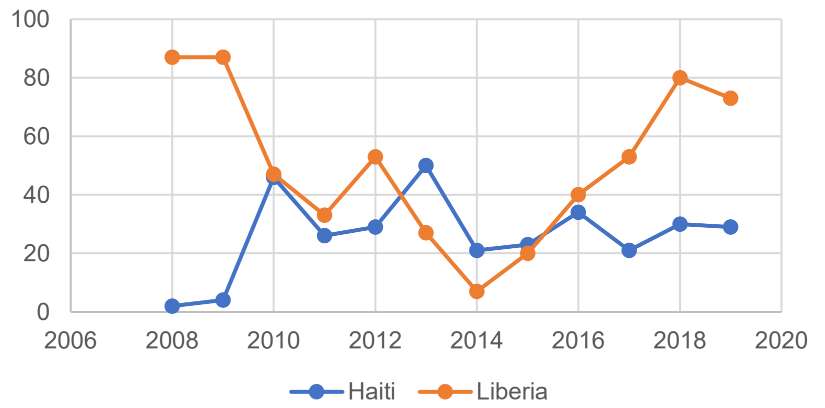


Figure 6. Proportion of Districts with at least 80% MCV1 Coverage in Liberia and Haiti, 2008-2019

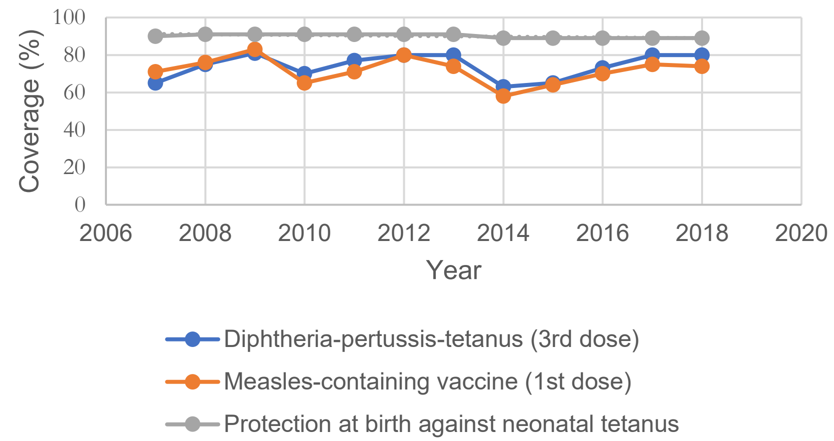


Figure 7. Health Service Coverage in Liberia, 2007-18

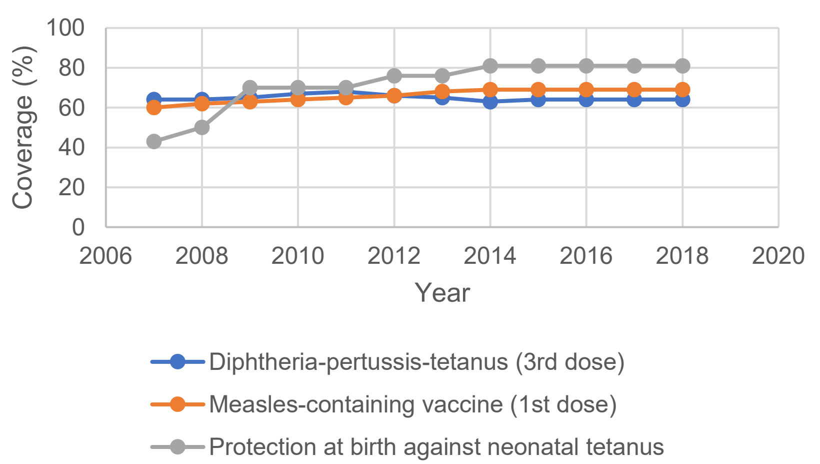


Figure 8. Health Service Coverage in Haiti, 2007-18

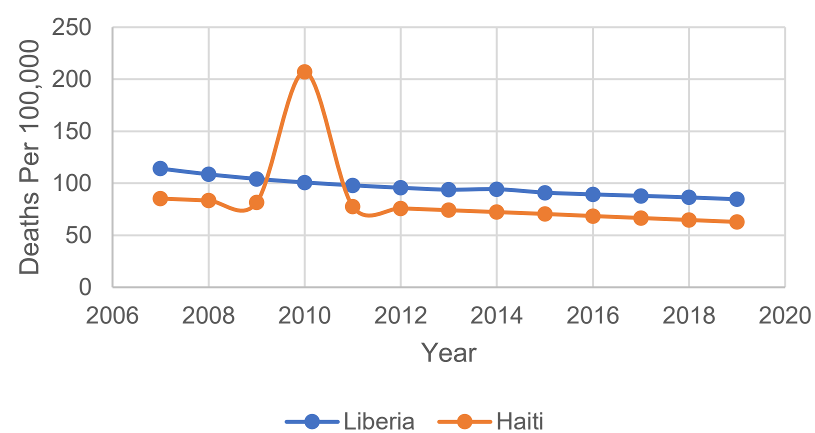


Figure 9. Under-5 Mortality in Liberia & Haiti, 2007-19

KI9 reflected on how MSPP and its partners scrambled, post-earthquake, to mitigate the risk of vaccine-preventable disease outbreaks:

> "If you look at the coverage level of routine vaccines immediately after…they had issues before the earthquake, but the earthquake just exacerbated them. So, they started low and then they just got lower…There was a whole measles, rubella, oral polio, Vitamin A, integrated campaign immediately after the earthquake, and then 2 years later as well…But we know that strengthening routine immunization takes longer – years. You can't do it overnight. But campaigns are a quick success and people want a quick win. But, also, some people are hard to reach, and they can't be reached by campaigns or routine immunization due to a rural area or distance or whatnot."

KI10 echoed these observations, highlighting challenges in post-earthquake immunization program implementation:

> "Everything was disrupted. We tried to provide routine services since the health system in Haiti has resources that are misused or is under-resourced. Vaccinating children is always a struggle…At the micro level, we were able to

> vaccinate some children in the district, but at the macro level, there were a number of barriers. There are issues with data quality, data collection, planning, and supervision of activities. Ministry of Health has the burden of vaccinating children but there are not sufficient numbers to cover the territory. They were also not well supervised."

Initial response efforts coordinated by external actors were similarly disjointed. MINUSTAH did not originally have a directive for humanitarian response, forcing the UN to belatedly amend its mandate.[208] The UN Office for the Coordination of Humanitarian Affairs (OCHA) also attempted to implement the cluster system in Haiti – an approach intended to delineate clear roles and responsibilities for actors across the broad spectrum of stakeholders and sectors involved in humanitarian response, including a health cluster led by PAHO.[218,219] Unfortunately, weak cluster leadership, poor inter-cluster coordination, and the vast number of NGOs and other stakeholders present in Haiti greatly complicated efforts to implement a cohesive, concerted response.[220] Additionally, twenty six countries deployed military troops to Haiti to support response efforts, but Haiti lacked the infrastructure to absorb the overwhelming influx of personnel, resources, and equipment.[208] OCHA later reported that the conscription of military resources for humanitarian purposes in Haiti may have violated the "principle of last resort"[§] articulated in its 1994 Oslo Guidelines.[220] Finally, many aid efforts appear to

[§] The principle of last resort articulated in the Oslo Guidelines ("Guidelines on the Use of Foreign Military and Civil Defence Assets in Disaster Relief") states that military and civil defense assets should be used to support humanitarian response efforts if "a specific capability or asset requirement that cannot be met with available civilian assets has been identified AND foreign military and civil defence assets would help meet the requirement and provide unique advantages in terms of capability, availability, and timeliness; AND foreign military and civil defence assets would complement civilian capabilities" (emphasis mine).

have focused on addressing the needs of hard-hit urban populations at the expense of assisting affected individuals in peri-urban and rural settings.[219]

3.4.1.3 The 2010s Cholera Epidemic: Impacts and Response

In October 2010, a group of Nepali MINUSTAH peacekeepers arrived in Haiti to support earthquake relief efforts. Epidemiological evidence suggests they had contracted cholera during MINUSTAH training in Nepal's Kathmandu Valley amid an ongoing outbreak, before arriving in Haiti without being screened for the disease.[221] Prior to the 2010s epidemic, cholera had not been reported in Haiti for over a century.[222] On October 21, MSPP's National Laboratory of Public Health detected the causative agent, *Vibrio cholerae*; and by October 27, 4,722 cases and 303 deaths had been reported.[223] Haiti's fragile water and sanitation infrastructure – further weakened by the earthquake – triggered rapid community transmission of cholera, which later prompted WHO to deploy oral cholera vaccines from its global stockpile to quell the outbreak.[224] Ultimately, the epidemic – which was finally declared over in 2019 – resulted in roughly 820,000 cases and claimed nearly 10,000 lives.[225]

According to KI4, the response to the cholera epidemic mirrored the initial disjointedness of earthquake relief activities, with donors and agencies frequently sidelining MSPP in favor of commandeering their own response strategies and implementing highly siloed surveillance, healthcare, and vaccination programs:

> "We were supposed to build 2,000 cholera rehydration points and about 100 or more cholera treatment centers. The donor

> didn't want to give money to the government, so they gave it to UNICEF with some checks and balances to the government…I tried to do [water, sanitation, and hygiene activities] and such, but when it was earmarked for emergency – you know, vertical response – I tried to go to the donor and make a case, but [they] said no way. It's earmarked for emergency response, you can do only A, B, C."

KI4 also observed that the outbreak had immediate impacts on routine health service coverage, recalling, "There was reduced access to essential health services, so paradoxically, it was better to get cholera than any other disease. It mostly had a negative impact on other essential health services. And the staff was redirected as well. All [community health workers, CHWs] working on other stuff were repurposed to cholera outbreaks." In 2013, MSPP and its partners launched a USD$2.2 billion strategy to eliminate cholera from Haiti ("National Plan for the Elimination of Cholera in Haiti") while simultaneously overhauling the country's public health system; however, by the end of 2014, 190 of the country's 250 cholera treatment centers had closed and 60% of the remaining facilities lacked adequate infrastructure.[226] The eventual exodus of NGOs from Haiti's health sector created a vacuum of health systems-strengthening resources and expertise: while as many as 400 organizations initially provided humanitarian aid, only 99 were conducting health activities as of 2011.[219] KI7 also framed the earthquake and cholera epidemic as missed opportunities for health system revitalization:

> "Haiti has been in crisis mode for so long that I'm not sure if the cholera outbreak changed that much. Things were barely functioning, and people were distracted before, anyways. If anything, cholera brought attention and resources into a regularly bogged down system. It was an incredible opportunity that wasn't captured super well…The biggest opportunity missed was that there were so many organizations working on stuff, and everyone had an agenda just for their thing, and resources just for their thing. And if those resources had been pooled, there could have been a much more concerted effort to invest in infrastructure, including facilities, and strategy for workforce, and all of that, but money wasn't shared or organized."

As KI7 noted, the collective devastation of the earthquake and cholera epidemic triggered an unprecedented influx of foreign aid, medical assistance, and humanitarian support. In 2009, for example, the United States alone disbursed just over USD$318 million in foreign aid to Haiti, including USD$98 million in "health and population" assistance and USD$52 million in humanitarian aid; the following year, these estimates soared to USD$1.3 billion, USD$100 million, and USD$680 million, respectively. Between 2010-16, the World Bank supplied over USD$100 million to support long-term reconstruction efforts.[227] In the three months immediately following the earthquake, Médecins Sans Frontières (MSF) treated 165,000 people, rehabilitated 10 hospitals, and constructed four new facilities.[228] The American Red Cross reportedly spent nearly USD$160 million on earthquake relief between January and June 2010 and subsidized 70% of Haiti's first oral cholera vaccination campaign.[229] [**] In sum, an estimated USD$13.5 billion from donor nations and private organizations was funneled into earthquake and cholera relief activities in Haiti, with the vast majority of funds channeled through the legions of NGOs, humanitarian agencies, and contractors operating in-country.[230]

3.4.1.4 Post-Cholera Routine Immunization Program Recovery

In March 2010, a few months after the earthquake, MSPP and its partners published an Action Plan for National Recovery and Development. This Action Plan, alongside the country's PDNA and cholera elimination plan, charted a path for health system recovery and enhancement, focusing primarily on reconstructing health facilities, rebuilding the country's health workforce, replacing lost equipment, and forging partnerships with the private sector to expand health service delivery. Though the cholera elimination plan alludes to improving "provision of vaccines, cold chains, equipment, and other supplies," details a plan to scale up oral cholera vaccination (OCV) campaigns and aims to eventually integrate OCV into the national childhood immunization schedule, routine immunization does not figure prominently in any of these recovery strategies.[212,231,232]

[**] A joint investigation led by NPR and ProPublica uncovered that the nearly half billion dollars that the American Red Cross purportedly raised for earthquake and cholera relief in Haiti was likely misappropriated. As of 2015, when the investigation was published, the Red Cross had allegedly constructed a mere six permanent homes with the funds.

By contrast, Haiti's EPI program developed a more detailed comprehensive multi-year plan (cMYP) for addressing routine immunization challenges following the 2010 earthquake. High-level priorities articulated in cMYP include improving governance of routine immunization programs; strengthening EPI capacities, especially in rural, peri-urban, and other marginalized regions of the country; and achieving financial sustainability to ensure long-term equitable access, quality, and safety of immunization programs.[216] cMYP also stated that EPI "should be used as a gateway to a minimum package of preventive, promotional and nutritional [services] targeting the dyad of the mother-child," underscoring the need for integrated approaches to health service delivery.[216] Sufficient funding for these efforts, however, would rely heavily on external partners and donors, including PAHO, UNICEF, Gavi, USAID, the Japan International Cooperation Agency, and Haiti's tripartite partnership with Cuba and Brazil.[216]

In addition to EPI's efforts to develop cMYP, MSPP worked with PAHO and UNICEF to devise a National Post-Disaster Vaccination Plan in 2010, which delineated a phased approach to increasing vaccination coverage and bolstering the country's routine immunization programs. In accordance with this plan, MSPP launched an integrated campaign in 2010 offering deworming tablets, Vitamin A supplementation, and vaccinations against measles, polio, diphtheria, pertussis, and tetanus. The first phase targeted residents of temporary settlements in the regions most affected by the earthquake, while the second phase expanded to all persons in these areas. By June 2010, over 900,000 people had been vaccinated, including 62% of the total population in the settlements and over 80% of children under five.[233] KI9 highlighted the logistical challenges associated with increasing routine coverage via campaigns, particularly as new vaccines were introduced into Haiti:

> "[The campaigns] were a good start to get kids vaccinated in the age range they had to be vaccinated. If you miss that age range in a campaign, they'll never get it. [But] then there was the push to add all these new vaccines…Then we had to know what rotavirus serotypes and diarrhea surveillance so we could assess impact from vaccination after it was introduced. We had to get cold chain back on board, since many fridges were not functional or destroyed after the earthquake. We had to monitor temperatures in the fridges before we could put vaccine in there. We had to worry about infection spreading in camps early on as well as importation of disease from people coming in."

Tohme et al. further report that these campaigns achieved lower levels of coverage in the western, central, and Port-au-Prince metropolitan regions of the country, due to children being away from home when vaccinators arrived, or to caregivers being unaware of the campaign.[234] Gavi also reported that a lack of proactive communication and messaging around the importance and value of vaccination – combined with poor patient experiences with healthcare providers – further undermined vaccine demand among populations targeted by the vaccination campaign.[235] Gavi further notes that capitalizing on missed opportunities for partnership – for example, between the country's EPI program, the Haitian Society of Pediatrics, the Haitian Red Cross, and the Haitian Platform for Civil Society Organisations to Strengthen Immunisation – could support improved immunization outcomes in the future.[235]

Additionally, though standalone campaigns aimed to meet nutritional needs in addition to offering vaccinations, cholera response efforts deterred other opportunities to provide immunization in a more integrated manner. When asked whether patients receiving cholera treatment were ever referred to a primary care provider for immunization, for example, KI5 answered:

> "It was identified as a good practice because when you come [to the cholera treatment unit], the family sometimes also comes, and you can go check. But what happens is that those spaces are physically distant, or there's red tape all over. I don't think it happened a lot where people said, 'oh, since I'm here, I'm going to go see my status and get my second dose of whatever,' because it was quite separated from the fear of cholera contamination… It's not like in the northern hemisphere where you drop someone [at the hospital] and you see them for an hour every once in a while; you have an investment and you feed them and take care of them in Haiti… So yes, referral would have been great, and it was identified as such, but it didn't happen often."

KI7 affirmed this observation, further reporting:

> "The cross-cutting theme I see people grappling with again and again is that the system isn't really a system. It's so many little pieces, and if even one of those pieces works – like, let's say there's a really good primary care level facility – even if that's working, that doesn't mean that the next level is working. That lack of continuity and ability to communicate to the population what to expect, and where to go, and how to navigate creates this sort of perpetuated lack of trust, and lack of paying attention at all, and why even bother?"

Following the campaigns, MSPP embarked upon the third and final phase of the National Post-Disaster Vaccination Plan: jumpstarting the country's national routine immunization program. KI8 shared that CDC, Brazil, Cuba, WHO, and UNICEF partnered with Haiti to place a medical consultant in each department[††] who was tasked with supporting vaccination and surveillance. Though intended to inject expertise into subnational immunization structures, this measure did little to resolve lingering challenges around human resource management and financing: "We lacked staff in place to provide vaccinations and [among] department staff. We didn't have many strong teams in terms of coordinating vaccination activities," continued KI8. "These

[††] A department is a subnational administrative division, of which there are ten in Haiti. Haiti's departments are further divided into 42 arondissements, 145 communes, and 571 communal sections.

department coordinators were also in charge of other programs, too, like nutrition, so that's why we had to add in the department consultant. So, to me, the human resources were a big problem." This observation is corroborated by Gavi, which describes poor technical coordination between departmental and central-level health authorities, difficulties scheduling regular meetings, and delayed reporting of statistical data during this period.[235] KI8 also described how a lack of consistent funding further undermined the sustainability of the country's precarious immunization infrastructure:

> "All the vaccines were funded by the partners. The national government was not putting any contribution on purchases of vaccines for the routine program…We had a meeting with World Bank, and they agreed to help on routine immunization. UNICEF and Japanese cooperation [were] supporting measles, but they pulled out…We had many meetings with ministers of health and finance; we had a transition plan for government to, year by year, take over funding; and we had support of the WHO AFRO office, and they brought experience from African country financing. We wanted the government to roughly take over one antigen per year so [that] in five or six [years], they could at least take over the basics – [Bacillus Calmette–Guérin vaccine], DTP, measles, pentavalent, and one other. I don't know how much

> progress has been made. But training and other costs are still supported by partners."

Elaborating further on Haiti's fiscal woes, KI6 highlighted a fundamental misalignment between Haiti's national health policy, donor priorities, and political will to conduct budgetary planning as the root cause of the country's health financing challenges:

> "The first issue is that the national health strategy in Haiti is all over the place. It allows a lot of flexibility, and there's a lot of talk among donors trying to coordinate so there's not duplication of funds. It's hard to measure donor alignment, though. But when you have a national health strategy, you match resources available with current priorities, determine funding gaps with priorities, and those types of tools are useful to make sure donor resources increase where funding gaps are, and make sure that donor resources align with this plan over time. Haiti was one of the main countries not interested in this kind of mapping, and we can't push them to do it. The government wanted to do it on their own without any help, but because the exercise isn't there, it's tough for people to understand where the gaps are. [Ministries of Health] in other countries do this on a regular basis."

Government ownership of health financing and policy – or lack thereof – was a recurring theme across both the key informant interviews and the literature. Per KI8, "The [immunization] program is owned by the partners. We did not see ownership at the national level, and they were not taking control of the immunization program. This was a big lack in Haiti, and it has to be addressed in order for there to be sustainability. We cannot just leave this problem to the partners." Both Tohme et al. and Dowell et al. echo this observation, underscoring the need to institutionalize immunization expertise and increase government health spending in Haiti, particularly amid competing donor priorities.[236,237] In some cases, however, MSPP appears to have been deliberately excluded from decision-making around immunization, as KI1 shared:

> "A lot of immunizations, routine or campaign, are being staffed by internationals, and very often, they do not speak Creole or French…If you are working on the ground – anything underneath the most senior level – you need to speak French or Creole…I've sat in meetings that were done in Spanish with no [MSPP] present, and they were taking key decisions within the public health sector for immunization…It's extremely important that the language and cultural fit [are] there."

The fragmentation of Haiti's health governance across a vast constellation of stakeholders – each with varying agendas, resources, and levels of capacity – gave rise to implementation challenges on the ground, particularly with respect to surveillance. Tohme et al. report that Haiti, with assistance from CDC, began scaling up surveillance systems in 2012, establishing a case-based system to monitor measles and rubella; four sentinel surveillance sites for detecting rotaviral diarrhea; another sentinel surveillance system for monitoring meningitis; and an environmental surveillance system for detecting both wild poliovirus and circulating vaccine-derived poliovirus.[236] Louis et al. also report that Haiti significantly scaled up its laboratory capacities during the same period.[238] Performance indicators for case-based measles and rubella surveillance (e.g., percentage of cases with adequate investigation, sampling, and laboratory processing) were largely positive between 2010-2015; in fact, Haiti moved from being ranked the fourth-worst performing country in the Latin American and Caribbean region to the sixth-best in terms of investigating suspected cases of measles and rubella.[236] Key informants nevertheless reiterated how governance and funding challenges undermined surveillance efforts – perspectives also echoed by Louis et al. and Tohme et al.[236,238] Similarly, KI9 noted:

> "If the government doesn't invest in their own workforce and their own program, external programs can't fund them forever. But the capacity of people who are there – it's really good, they know what they're doing and the information. But some of them were complaining that they don't have a car to go investigate a case of measles, or they don't have a computer. The minimum requirements of them doing their

job are not available to them. That leads to more weakness. The coverage in Haiti just went down again as well because there's no sustainability in the funding."

KI1 also cited political instability and violence as a deterrent to MSPP-led routine surveillance, noting that gang violence and limited transportation options often impeded case detection:

> "No one voluntarily goes into the country to do surveillance right now. Up until six years ago, CDC had a sort of shadow system of surveillance in the country that was more reliable, which is often the case, but I don't know if they continued that. Even if they do, they still have very limited resources and the last section that can do surveillance is WHO and UNICEF. I've not really seen a very well-equipped surveillance system from those two organizations in the country. It's very difficult, so for measles it has to be a big outbreak before it becomes notable, as is the case with other diseases as well. If it isn't big, it doesn't get observed."

During this time, Haiti did make significant progress in bolstering its public health laboratory infrastructure. Its Laboratoire National de Santé Publique (LNSP; "National Public Health Laboratory"), established in 2006, initially lacked a strategic plan and focused primarily on HIV diagnostic capacities; advanced testing was often outsourced to NGOs or private-sector partners like GHESKIO Center.[238] Following the earthquake, laboratory facilities within the earthquake's epicenter suffered considerable losses.[238] With support from the U.S. government, Haiti transformed its nascent laboratory network into a tiered, pyramidal system with expanded confirmatory testing capacities, a national strategic plan, training curricula for laboratory personnel, and forthcoming legal and regulatory frameworks for licensing, accreditation, and quality management.[238,239] However, with the near-entirety of the network's funding coming from the President's Emergency Plan for AIDS Relief – and the need to outsource equipment maintenance and repair to external contractors – the sustainability of this laboratory system remains uncertain.[238]

In addition to laboratory and surveillance challenges, data deficits hindered efforts to conduct routine immunization microplanning activities, forecast vaccine supply and demand, and measure vaccination coverage. “There are quality issues; not everyone is collecting data the same way,” remarked KI5. “We aren't collecting it for a census, we're just collecting it to help a program. Microplanning comes from the base of pyramid, and the base struggles.” Similarly, when asked about microplanning, KI3 reported that such activities are largely supported by UNICEF and take place at individual facilities. “I have an Excel sheet and if you click on the name of the facility, you have all the information about microplanning,” they stated. “Microplanning is really well done, but the target population is the issue. Knowledge, skill, and experience goes into great planning, but if you don't know the number of people you're serving, your great microplanning doesn't matter.”

Like many low- and middle-income countries, Haiti struggles to estimate health service coverage due to out-of-date target population estimates.[240] "The last census we had in Haiti was in 2003 or 2005. That was about 20 years ago," KI3 pointed out. "The only thing we were able to do as a country was apply formulas to estimate present and future population. We don't have the real population of Haiti, though – we're just applying a percentage to estimate the births. We need to actually count the amount of children every year or so to estimate vaccination coverage." While inaccurate population estimates compromise the denominator of Haiti's coverage calculations, poor documentation of vaccinations administered distort the numerator, further contributing to artificially low coverage estimates. "The private sector with the physicians…are the hospitals that are vaccinating the most children in the country, but they are not reporting those numbers in DHS," noted KI3. "To speak clearly, we don't know what vaccination coverage is actually. There is a data issue with big hospitals vaccinating lots of children and not reporting in the database. I know one hospital that vaccinates thousands of children per year that doesn't report." KI1 added that poor vaccine forecasting can be especially costly in a place like Haiti: "It's also not how many [vaccines] you need, really. It's how many you can use, because if you don't have a cold system, then what is going to be your trade-off? How many vaccines do you dare to distribute? Because you get an issue vaccinating with ineffective vaccine – with water – or you have to risk destroying vaccine, which is expensive. Even if the vaccine isn't expensive, the logistics of getting it from the capital to the countryside is expensive." Gavi further reports that poor data-sharing practices between departmental- and central-level authorities impedes planning and decision-making around immunization, “thereby not encouraging the emergence of strategies to improve immunisation coverage and equity in Haiti.”[235]

Unreliable coverage estimates, in turn, complicate efforts to forecast vaccine demand – a challenge that KI3 suspects is motivated in part by politics and perverse financial incentives:

> “I hear this at least ten times a year – an implementing partner complaining they only [get] two thirds of the doses they requested. So, after three years of receiving two thirds, two thirds, two thirds, a new cohort of children is created for a campaign. If facilities are only receiving two thirds of what they request, we’ll never get over 66% coverage. And that’s the maximum. We have no idea why they are getting only two thirds. I feel that [MSPP] fears to ask this question to PAHO. I would love to ask at the table, but if I ask, I could lose my job – other people have. Those people are so powerful, they can even cut the head of ministries.”

On this point, KI9 acknowledged that “the salary is low or nonexistent for routine immunization, while the money is made from campaigns – which come from outside funders. So, the government really doesn’t give much money from themselves for immunization.”

In this vein, workforce issues – particularly compensation and job satisfaction – permeated both the literature and key informant interviews as a major barrier to routine immunization program recovery. “Compensation and salaries are an issue because salaries are really low in the public sector, and it’s really a lot of work,” shared KI2. “Sometimes, at a health institution, you have very little staff expected to do everything. Any time something new comes in, then it’s added work. So, there’s constantly issues with workload unrelated to compensation and that does affect satisfaction and that’s at all levels from entry-level to management.” The near-constant, kaleidoscopic shifting of Haiti’s donor landscape has further destabilized the country’s health sector job market and fueled health worker discontent. On this point, KI6 shared:

> “There’s no clear allocation formula by which the government determines the health budget – it’s very input-based. The central level provides salaries to health staff by department directly. District health workers go to the health district to receive their salary. That’s really what the Ministry of Finance is in charge of. They send the money to the representation of [MSPP] at the district level. And the rest, there’s hardly anything. Salary represents about 90% of total budget in the health sector, the rest is hugely subsidized by donors. Not much is going there because they don’t have a big budget, they spend $2-3 per capita on health, I think. I don’t think there’s a formula to allocate budget to district

> based on needs – they are far from that, it's not there. And it has always been like that, so it's a key impediment to funding services like immunization. Apart from that, the non-salary budget line isn't really funded by the government."

MSPP's overreliance on donors has resulted in considerable levels of health worker attrition from the public sector, especially given that private sector entities generally offer higher wages and more robust benefits.[203] Hashimoto et al. also report dissatisfaction with placement in remote geographic areas, high turnover, and chronically delayed payments as additional challenges plaguing Haiti's public sector health workforce.[241] Finally, KI1 stressed the importance of contextualizing workforce challenges within the country's broader social, political, and cultural milieu:

> "You also have to pay health resources per diem. And you hear 'oh, it's for their own good and it's a benefit they should appreciate," but you're talking to people who most likely haven't been paid for a year, and people who have been offended over and over again, and they want to feed their own children, and they'll do that with the $150 for vaccinating for five days. And if you don't pay them, they won't do anything because they've been offended before."

3.4.2 Liberia

3.4.2.1 Historical Overview

Like Haiti, Liberia's colonial roots serve as prologue to its present-day health system challenges. Originating as a project of the American Colonization Society (ACS) – a U.S. group that advocated for the repatriation of free Black Americans to Africa – Liberia first consisted of settlements affiliated with individual American states, including Mississippi-in-Africa, New Georgia, Kentucky-in-Africa, and Maryland-in-Africa, among others.[242] ‡‡ Support for the Society's mission stemmed, in part, from a desire to minimize the U.S. population of free Black Americans and avert potential slave rebellions. In a striking parallel to America's occupation of Haiti nearly a century later, many ACS leaders also envisioned themselves as humanitarians, albeit acting under divine mandate. Nevertheless, they continued dispatching freedpeople to Africa despite full awareness that Americo-Liberians were dying in large numbers from tropical infectious diseases.[243,244] In the 1940s, the U.S. launched a Public Health Mission in Liberia to tackle the country's high prevalence of infectious diseases, reorganize the country's then-Bureau of Public Health and Sanitation, and train the local health workforce.[245] The purpose of these missions – civilian in name but militarized in their execution – was to "survey Liberian natural resources and create a healthy environment for postwar development and export through an American-controlled harbor."[246] Asserting that a fully autonomous Liberia would collapse into financial ruin after World War II and contribute little to the global postwar economy, the U.S. later sought to

‡‡ Notably, Maryland-in-Africa – later known as the Republic of Maryland – was founded by freeborn African-Americans from Maryland and existed as an independent country from 1834-1857 before being annexed into present-day Liberia as Maryland County. Baltimore City was a major embarkation point for freedpeople in the U.S. departing for Africa.

manipulate Liberian domestic reforms by controlling the flow of aid into the country, thereby "developing capacities of the people for whose benefit it was intended."[246]

Two modern-era health crises have played a direct role in shaping Liberia's post-Ebola routine immunization successes: the First and Second Liberian Civil Wars. During the First Civil War (1989-1997), Samuel Doe – the Liberian president and former general who had seized power through a violent coup – was brutally executed by a rebel leader, Prince Johnson. Following a power struggle between Johnson's forces and another faction led by Charles Taylor, a ceasefire in 1995, and a national election in 1997, Taylor was eventually inaugurated as the 22nd President of Liberia.[247] Just two short years later, however, the Second Civil War erupted. Two rebel militia groups – Liberians United for Reconciliation and Democracy and the Movement for Democracy in Liberia – emerged in the northern and southern regions of the country, respectively, before usurping power from Taylor.[248] After years of violence, Taylor's resignation, and months of negotiation, the warring factions signed the Accra Comprehensive Peace Agreement in 2003, ushering in a two-year transitional regime led by Gyude Bryant.[249] Women of Liberia Mass Action for Peace – a movement organized by Leymah Gbowee, Crystal Roh Gawding, and Comfort Freeman – was a major driving force behind brokering the 2003 peace agreement.[250] This movement was also instrumental in electing Ellen Johnson Sirleaf, Africa's first female head of state, to the Liberian presidency in 2005.

3.4.2.2 Postwar Health System Reconstruction

Years of civil war wrought devastation upon Liberia's public health and healthcare infrastructure. Of the country's 550 pre-war health facilities, only 233 functional public facilities (12 hospitals, 32 health centers, and 189 clinics) and 121 functional private facilities (10 health centers and 111 clinics) survived the conflict.[251] The wars had also decimated Liberia's health workforce: in 2002, there were only 4,000 full-time and 1,000 part-time staff serving a population of roughly 3 million people, including 168 physicians, 273 physician assistants, 453 registered nurses and more than 1,000 nurse aides and other health professionals – far short of the WHO-recommended minimum health workforce density of 4.45 doctors, nurses, and midwives per 1,000 people.[252,253] Population health suffered considerably as a result of this workforce attrition and health facility destruction. In 2007, for example – four years after the Second Civil War ended – a mere 23.5% of Liberian children were fully immunized, including only 9.3% of children in the poorest wealth quintile.[254] As KI20 shared:

> "The immunization program got its boost from the rollout of the global polio eradication initiative. A lot of the support at that time was centered around that initiative so countries were more reliant on polio eradication as a means of supporting the entire health system…During that time, we had very frequent [vaccine-preventable disease] outbreaks and immunization coverage was still low. Pre-Ebola Liberia was still trying to recover from the post-civil war crisis and

> gradually trying to reconstruct the health system. There [was] still that massive degree of fragility and we [had] just gotten a newly elected President, one we consider a democratic President out of the conflict of Liberia."

KI14 corroborated this observation, adding:

> "Pre-civil war, we may [not have] had health infrastructure across the country, but health services were affordable. We had highly trained and specialized health practitioners and physicians. When the war emerged, these practitioners fled the country, putting a strain on the health system. Afterwards, the health [sic] was assumed by international civil organizations…They took over for the government on providing health services. When the war eased off, there were difficulties with the workforce, so there was a loss of capacities with some people integrated into the new workforce and others not."

Figures 6, 7, and 9 illustrate trends in immunization coverage and under-5 mortality in Liberia during its pre- and postwar periods.

Recognizing the need to overhaul the country's postwar health system, the Liberian government embarked upon an ambitious agenda to dismantle barriers to healthcare access and increase health service coverage. In 2007, the Ministry of Health and Social Welfare (MoHSW) released its National Health and Social Welfare Policy and Plan, which articulated a vision for "a Liberia with improved health and social welfare status and equity in health; therefore [sic] becoming a model of post-conflict recovery in the health field."[255] To that end, the document laid out plans for a Basic Package of Health Services (BPHS) – a free suite of core services addressing vaccine-preventable diseases, nutrition, maternal and reproductive health, sexually transmitted infections, tuberculosis, malaria, and HIV/AIDS, among other conditions – with plans to gradually scale the package up to at least 70% of health facilities by the end of 2008.[255] As part of this effort, MoHSW formed a human resources unit to coordinate training programs for nurses and mid-level providers; it also established a Health Sector Pool Fund in 2008 to streamline government, donor, and NGO contributions to BPHS implementation.[256,257] Though only 36% of public facilities were fully BPHS-accredited in 2008, this estimate eventually rose to 80% by the end of 2010.[175] However, there were lingering concerns that BPHS did not sufficiently integrate services across the full spectrum of maternal and child health programs, thereby encumbering delivery of some maternal health, nutrition, family planning, and mother-to-child prevention of HIV services.[258]

In light of these shortcomings, MoHSW subsequently launched an Essential Package of Health Services (EPHS) in 2011. EPHS broadened the scope of BPHS to encompass care for noncommunicable diseases, dental and eye care, and neglected tropical diseases; created a tiered structure for primary, secondary, and tertiary service provision; and strengthened referral mechanisms to improve health system efficiency.[259]

Notably, the Global Polio Eradication Initiative (GPEI) played an important role in bolstering Liberia's weakened routine immunization program during this time. As KI21 observed:

> "EPI started in Africa, and Liberia was one of those early countries, but it was basically in 2004 before the immunization program got strong because of polio eradication. [From] 2000 to 2004, Liberia started a robust polio eradication program and that really strengthened routine immunization program and the health system…When the war was over and the first national health program was crafted in 2007, immunization was part of the essential package of health services. Then community engagement and everything else was strengthened."

Despite these developments, however, government health spending remained low during the immediate postwar period, fluctuating between USD$4 and $13 per capita from 2003-2010; meanwhile, out-of-pocket expenditures comprised between 50% and 75% of total health spending during that same period.[215] Other key health indicators, such as under-5 mortality and national immunization coverage, improved, albeit slowly (see Figures 6, 7, and 9).

3.4.2.3 Response to the 2014-16 West Africa Ebola Epidemic

In December 2013, an index case of Ebola virus disease (EVD) was diagnosed in an eighteen-month-old boy in Guéckédou Prefecture, Guinea.[260] Health authorities detected additional cases among other residents of the prefecture, and later, in the capital city of Conakry. On March 23, 2014, following reports of 49 confirmed cases and 23 deaths in Guinea, WHO declared an outbreak.[260] The very next day, the Liberian Ministries of Information, Culture, Tourism, and Health announced six suspected cases of Ebola in the country, of whom five had already died.[261] Over the next two years, the outbreak rapidly escalated to 10,678 cases and 4,810 deaths in Liberia before authorities officially declared its end on June 1, 2016.[260]

Early in the epidemic, health officials in Liberia and their international partners[§§] created an Ebola Task Force to coordinate a swift response. However, the Task Force soon proved to be too unwieldy. “When EVD emerged, it took a political dimension in terms of leadership. There wasn’t a technical person providing insight but rather a political structure,” recalled KI14. “There was mixed messaging. There was conflicting information [until] the U.S. was able to intervene by…providing accurate information to the public in regard to EVD prevention and control. Then the government could change its strategy for control and prevention by bringing in and respecting the roles of the local leaders and practitioners.”

Liberian authorities ultimately adopted the Incident Management System (IMS) instead: a standardized protocol developed in the United States for coordinating

[§§] Key partners included CDC, WHO, the U.S. Agency for International Development, the International Federation of Red Cross and Red Crescent Societies, Médecins Sans Frontières, Samaritan’s Purse, and Global Communities, among others.

emergency response activities.[262] Liberia chose to coordinate IMS activities through a new, donor-funded emergency operations center – which, after the Ebola epidemic, was used to monitor outbreaks of other vaccine-preventable diseases like meningitis.[263,264] "We had people in health communications, logistics, [and] supply chain all falling under the incident management system that [was] a replica of the CDC system," shared KI21. "We had Liberian leadership within each thematic area. EPI, surveillance, contact tracing, laboratory, health communications, case management, etcetera – those were all thematic areas. [And] we had international partners embedded in each of these thematic areas." President Sirleaf communicated frequently with the designated incident manager and established an advisory committee comprised of senior officials and international partners to guide response efforts.[262]

KI21 also attributed Liberia's post-epidemic success in routine immunization to IMS, stating, "The collaboration and coordination was difficult at the beginning of [Ebola]. In [MoHSW], there was the health coordinating committee, but they were very high level. They weren't prepared for emergency response; they just [had] meetings. IMS worked, so we wondered if that [could] restructure the health care system, especially with community engagement being so critical." Similarly, Brault et al. write that "the Liberian government's relationship with donors had evolved such that donors no longer drove the agenda, but rather accepted guidance from the government on priority areas and needs that the donors could assist with."[258]

Notably, government health expenditures in Liberia grew to USD$65 per capita in 2014 (from USD$59 per capita in 2013) and increased to USD$70 per capita in 2016, the final year of the epidemic.[215] The country also saw an influx of funds from donors and external partners during this time. In 2013, for example, the U.S. government had disbursed USD$34 million in foreign assistance to Liberia, which was earmarked for health and population needs; this allocation grew to USD$37 million, USD$49 million, and USD$71 million in 2014, 2015, and 2016, respectively.[176] U.S. humanitarian assistance to Liberia also skyrocketed from a mere USD$6.7 million in 2013 to USD$310 million in 2015. Additionally, over USD$170 million was obligated by various United Nations (UN) agencies and international organizations to support regional response efforts via the UN's Multi-Partner Trust Fund.[265]

3.4.2.4 Routine Immunization Challenges

The Ebola epidemic had immediate, destabilizing effects on population health and health system functioning in Liberia, as KI19 described:

> "Before the outbreak…there was an effort on peace, calmness and rebuilding. Immunization was ramping up like any other system. All the systems were building up. We'd quadrupled the number of functional health facilities in the country. Every health facility had at least two professionally trained workers…When EVD came in, it took us back many years. The whole system collapsed again. During the EVD outbreak, you could not find a functioning health facility. The whole country shut down. Even [those] who went to health

> facilities, they were refused. They may not have died of EVD, but they died of health issues that went untreated."

Similarly, KI19 shared, "There were immediate disruptions because even before EVD there was a problem with access to health facilities and lack of coming back for second dose follow up. The health of the child is sole responsibility of the mother and not the fathers. So, we'd have low coverage and health facilities were underutilized. We didn't really have a well-structured data system either. There were few people trained in data collection and data management."

When asked whether routine immunization campaigns continued during this time, KI15 responded with an emphatic "no": "Nowhere. Schools were closed, campaigns were withheld. Communities were not allowed to converge in large groups and health workers didn't go into communities. If a mother voluntarily brought in her child for vaccination, then [the] child was vaccinated, but no campaigns took place during EVD." Clarke et al. corroborate this observation, reporting that all planned outreach, introductions, campaigns, and supplemental immunization activities were temporarily paused. Additionally, MoHSW staff – many of whom were diverted from routine programs to Ebola response activities – were subsequently unable to implement EPI workplans. With fewer than 70% of health facilities open, fear of contracting EVD in healthcare settings also caused public demand for health services to plummet.[266]

These setbacks sparked a rapid decline in routine immunization coverage across Liberia (see Figure 6). Vaccination equity also suffered as a result. In 2013, 62.2% of Liberian children aged 24-35 months in the wealthiest quintile and 25.4% in the poorest quintile were fully immunized; in 2016, these estimates fell to 5.2% and 3.7%, respectively.[254] KI17, who began working in Liberia in 2017, also highlighted geographic inequities, noting, “The biggest challenge was the issue of equity in immunization…When you dive deeper into the disaggregated data, there were still counties with low coverage.” Wesseh et al. echo this observation, finding that the counties most affected by Ebola (i.e., those reporting more than 70 Ebola deaths) reported 58% fewer fully immunized children during the epidemic; moderately affected counties (10-70 Ebola deaths) and least-affected counties (<10 Ebola deaths) reported reductions of 33% and 39%, respectively.[267] KI20, who coordinated immunization activities in counties heavily affected by the epidemic, also highlighted negative externalities associated with introducing Ebola vaccines:

> “It was evident towards the end of the response that the number of measles cases were exponentially high and out of the windows. What also complicated the entire situation was the introduction of the EVD vaccine. The myth was out there that the vaccines available at the hospital or health facilities were EVD vaccines, so the EVD research vaccine introduction was a real issue. The entry of that was not properly executed. That really hindered the immunization program. As a result, we had to conduct two or three rounds of [supplemental immunization activities, SIAs], and even after that, we still had a number of cases among children

> over five or ten years raging [sic]. We had to then conduct a campaign targeting those ages."

3.4.2.5 Post-Ebola Routine Immunization Program Recovery

Despite major disruptions to routine healthcare delivery, health authorities made efforts to prioritize routine immunization activities even during the early days of the epidemic. "Two or three months after EVD started, there were technical guidelines issued to bring the attention back to the immunization program as much as possible and reassure health workers to give them minimum measures to provide safe immunization services," recalled KI12. "Those technical guidelines were really helpful for bringing back political attention and providing some confidence in routine immunization programs." Contrasting the Liberian approach to routine immunization with those adopted in neighboring Ebola-affected countries, KI12 further noted:

> "Guinea was the worst in this regard because their coverage level fell quite precipitously, just like Liberia. Their administrative coverage figures were falling significantly, but they didn't bring focus back to it like Liberia. There were a lot of delays in bringing attention back to immunization, and the country paid dearly for that with protracted measles outbreaks and many months with service delivery falling. For Sierra Leone, even though we felt that the risks were equally bad, they kept showing us administrative coverage figures

> that were the same as the pre-Ebola period. They kept telling us they were fine and there was nothing to worry about. And when you have faulty data coming from the field, you can imagine how misleading it can be to take the necessary precautions. In terms of long-term impact, they also faced significant and protracted outbreaks that didn't stop even after interventions."

Liberia's post-Ebola routine immunization efforts also owe much of their success to proactive planning, effective leadership, and increased investment in health system recovery. As early as December 2014, for instance, Liberian health officials participated in a high-level meeting on strengthening health system resilience in Ebola-affected countries, followed by consultative meetings with stakeholders involved in the ongoing response to achieve consensus on recovery priorities.[268] Next, MoHSW created thematic working groups in alignment with WHO's health system building blocks framework: leadership and governance; service delivery; financing; workforce; medical products, vaccines, and technologies; and information systems.[269] Each working group was comprised of MoHSW senior staff and external partners (including those from outside the health sector), and regularly reported to the Cabinet of Liberia to keep the country's executive branch apprised of recovery efforts. Working with senior MoHSW leaders, the working groups also performed a detailed situational analysis to identify priority areas for Ebola recovery.[268]

These planning efforts, in turn, formed a robust policy foundation for post-epidemic health system recovery. Liberia's Economic Stabilization and Recovery Plan, for example, explicitly connects the country's economic recovery to health system recovery, reporting that between 2015 and 2017, a total of USD$456 million would be spent on implementing the provisions of an Investment Plan for Building a Resilient Health System ("the Investment Plan"): strengthening the health workforce (USD$121 million), reengineering health infrastructure (USD$115 million), epidemic preparedness and response systems (USD$33 million), medical supply and diagnostics management (USD$58 million), enhancement of quality delivery systems (USD$111 million), information and research management (USD$2 million), community engagement (USD$5 million), leadership and governance (USD$7 million), and financing systems (USD$4 million).[270]

The Investment Plan and several other policies and strategic plans – the National Health and Social Welfare Policy and Plan 2011–2021 (NHSWP), the National EPI Strategic Plan 2016-2021 (i.e., the comprehensive multi-year plan, cMYP), and the National Action Plan for Health Security (NAPHS) – all feature provisions for strengthening routine immunization services and systems in the wake of Ebola. NHSWP, which was formulated prior to the Ebola epidemic, designates clinics as the basic units of Liberia's primary healthcare system and the main points of delivery for EPHS, including routine immunizations.[175] NHSWP also affirms Liberia's commitment to implementing the Reaching Every District strategy – an approach championed by WHO, Gavi, and UNICEF for improving immunization coverage in low-performing jurisdictions – while supplementing routine programs with SIAs and National Immunization Days.[175]

Liberia's cMYP, meanwhile, articulates several ambitious targets: increase national coverage of three doses of the pentavalent vaccine from 71.4% (as measured in 2013) to at least 90%, with at least 80% coverage in all counties; and reduce measles mortality by 90% by the end of 2020 (relative to 2000). Other goals include elimination of vaccine stockouts during 2016-2020, improving the country's cold chain system, supporting provision of an integrated health service package as specified in NHSWP, and bolstering immunization workforce capacities.[271] Liberia's cMYP also features detailed SWOT (strengths, weaknesses, opportunities, and threats) analyses of various facets of immunization programming, including service delivery; logistics and vaccine management; advocacy, communication, and social mobilization; surveillance; monitoring and evaluation; program management; financial sustainability; and human resources and institutional strengthening.[271] cMYP also provides timelines, objectives, and indicators for each planned immunization activity, along with detailed cost estimates.

Like cMYP, NAPHS – which was developed as part of Liberia's participation in the Global Health Security Agenda – costs out prioritized capacity-building activities (including just over USD$4 million for immunization) and echoes cMYP's commitment to scaling up coverage and human resource capacities.[272] Notably, both documents also underscore a commitment to equity: cMYP highlights the Government of Liberia's obligation to "ensure equal access to quality EPI services," while NAPHS purports to "strengthen equity focus analysis and programing for immunization service delivery."[271,272] Finally, Liberia's 1976 Public Health Law – which was revised and approved in 2019 – includes a dedicated chapter on immunization, which specifies leadership roles and responsibilities, articulates guidelines for vaccine management, outlines vaccination requirements, and details financial arrangements for the EPI program.[273] Close alignment and linkages between these foundational documents, policies, and laws facilitated a cohesive approach to resurrecting Liberia's routine immunization capacities following the Ebola epidemic.

Support from external partners also played an important role in post-Ebola immunization program recovery. "World Bank was very helpful," KI18 recalled. "USAID had also started providing financial support with the Liberian government managing it directly rather than passing it through NGOs. [MoHSW] used that as a reimbursement mechanism. It had to be spent on earmarked areas identified by both governments. The [MoHSW] and Ministry of Agriculture were the main benefactors of that money, and it included bolstering immunization and primary health care." Additionally, Gavi provided Liberia with nearly USD$3 million as part of a dedicated Ebola EPI Recovery Plan.[274] This and other Gavi funding streams were instrumental in implementing SIAs, increasing uptake of new and underused vaccines, strengthening Liberia's health system, and supporting Liberia's urban and non-urban immunization strategies – core components of the country's plan to ensure equitable coverage across all counties.[275,276]

Liberia's deteriorating physical infrastructure, which remained in poor condition following the Civil Wars, presented major obstacles to immunization outreach and delivery after the Ebola epidemic. KI11, who began working in Liberia in 2018 reported, for example, "The lack of infrastructure was terrible there – roads and electricity or lack thereof had the biggest effect on health systems…I'd never seen roads so bad. There used to be electricity and hydro dams and waste treatment in the seventies, but it was all destroyed intentionally during the war…Afghanistan is the most expensive place [in the world] to build roads, but Liberia is close."[***]

KI19 underscored the importance of external partner support in overcoming infrastructural challenges, sharing, "With partnership from Gavi, UNICEF, WHO, there were a lot of trainings conducted at both the national and subregional levels, so people knew what to do. Technicians for cold chain were trained and retained and got logistics like motorcycles." Cold chain challenges had previously hindered vaccine management and delivery; Gavi, in fact, reported that resource-shifting to accommodate the Ebola response caused cold chain equipment to break down in 2014, and UNICEF dispatched teams to perform repairs in 2015.[277,278] Gavi support in 2017 later enabled Liberia to train 17 cold chain officers, construct two regional cold stores, and procure two cold vans to facilitate vaccine delivery.[275] Between 2016 and 2018, Gavi funds also subsidized 248 solar direct drive refrigerators to further expand the country's cold chain capacities.[275]

In addition to shoring up vaccine delivery infrastructure in the wake of Ebola, Liberia bolstered surveillance for vaccine-preventable diseases – measures that enabled health authorities to monitor disease incidence trends more effectively, informed immunization campaigns, and enhanced preparedness for outbreaks. KI20 credited prewar GPEI efforts with initially scaling up the country's fledgling surveillance systems:

[***] Building a single sixty-mile road in eastern Afghanistan in 2014 cost roughly USD$5 million per mile, due largely to the cost of providing security for construction workers, per Washington Post. A 2020 news report indicates that the cost of building asphalt or concrete roads in Liberia runs between USD$1-1.2 million per kilometer, the same estimate reported by NPR in 2010.

> "In times past, there were surveillance systems across the country with diseases having their own structure and system – malaria, TB, etc., and EPI would do the same with all those different diseases. But with the introduction of GPEI, we introduced a more radical structure. At the county level, there was a surveillance officer and at the national level there were surveillance officers. Then we also had a local presence in communities of interest. These resource persons were focal points such as traditional healers, spiritual healers, and the rest of it."

However, the Ebola epidemic illuminated critical vulnerabilities in these nascent systems. "We realized that we had to make a reform in the human resource structure for surveillance in Liberia," recalled KI20. "We had to build capacity, look at infrastructure for public health surveillance and diagnostics, and the number of tests that we could conduct in Liberia was far less…Liberia could not perform tests for Lassa, EVD, or yellow fever – a good number of them except for measles."

These deficiencies became apparent early in the Ebola epidemic. In September 2015, a group of experts from MoHSW, WHO, and CDC met in Buchanan, Liberia to discuss improved implementation of the Integrated Disease Surveillance and Response (IDSR) platform.[279] WHO originally conceptualized IDSR in 1998 to help African countries strengthen surveillance, laboratory, and response capacities in alignment with the International Health Regulations (2005); the system had been adopted in Liberia in 2004, albeit without a strategic implementation plan.[279,280] During the 2015 meeting, however, participants conducted a SWOT analysis of existing capacities and produced a plan titled "Development of the 5-Year IDSR Strategic Plan for Liberia," along with a corresponding monitoring strategy.[279] Liberia also benefited from substantial external investment in surveillance-strengthening activities:

> "We had a lot of support come in from donors during EVD, so the surveillance system was highly donor-driven, certainly from the technical side and a lot from the financial side as well," reflected KI15. "We had a lot of support coming from China, coming from USAID, and other organizations that were supporting the surveillance system. Most of our health system was donor-driven. [MoHSW] was the technical arm, but financial was [sic] carried by partners – surveillance, supplies, training of workers, training of support staff."

These efforts to revitalize IDSR ultimately proved fruitful: improved surveillance, coupled with robust community engagement, facilitated a successful measles immunization campaign among children under ten and improved early detection of both measles and acute flaccid paralysis following the Ebola epidemic.[281,282] In addition to IDSR, Liberia also adopted the Early Warning and Response Network (EWARN) system, a WHO-prescribed approach for gathering data on acute, rapid onset crises like epidemic-prone disease outbreaks.[283] However, Clarke et al. reported that the presence of parallel surveillance systems running alongside IDSR revealed discrepancies in the data being collected – a challenge also reported in other African countries.[266]

Surveillance capacity-building dovetailed with strong commitments to accelerating social mobilization and expanding community outreach during the Ebola epidemic. Community-based surveillance, for example – whereby grassroots informants were enlisted to alert health authorities to suspicious illnesses or deaths – proved to be an effective deterrent to Ebola transmission.[284] Health authorities later adopted this model to measles outbreak containment efforts following the Ebola epidemic.[281] Encouragingly, surveillance protocols established during the epidemic were also institutionalized in routine public health practice, according to KI16:

> "The good thing about EVD is that when it [came] to surveillance, the establishment of the surveillance system was interconnected. When EVD surveillance happened, there was support for communication and whatnot. Specimens would go to the lab to get tested and we would hear about that during our daily case counts. And through that, we could hear about polio conditions and immunization conditions. So now, that system in place helps us and…captures all reportable diseases."

Rebuilding public trust in routine immunization services, after Ebola, however – particularly among the hardest-hit populations – proved to be a daunting challenge.[285] "It was difficult. No one was going up for surveillance or vaccine," continued KI16. "People were not coming to the health facilities; they were afraid of [healthcare workers, HCWs] infecting [the] general public. HCWs were also afraid of the general public infecting them." Liberia's linguistic diversity further impeded immunization outreach, according to KI11: "People don't speak the same languages fifteen minutes apart – entirely different languages, not different dialects. From my understanding, that was because people were so limited in movement during the war. You can't even sell tomatoes to your neighbors. That makes problems for vaccinators and nurses because they can't talk to their patients, there's no common language. How are you supposed to do health education without a common language?" Linguistic challenges notwithstanding, KI13 asserted that the positive legacy of the EPI program in Liberia set the tone for the country's post-epidemic immunization activities:

> "The immunization program is one of the oldest programs in the Ministry. They've been involved in primary health care for more than four decades now. They've done a lot of work around awareness creation and their messages on the issue of vaccinating children have resonated very well with the population. So, when you talk about a rural parent in Liberia talking about immunization, [it's] because there's frequent

> awareness on polio and integrated campaigns – they do two or three per year."

Confronted with the tasks of scaling up both trust and immunization coverage after Ebola, public health authorities coupled mass messaging approaches with grassroots strategies adapted to local contexts:

> "There was a UN mission in Liberia [with] a radio station that provided wide coverage, but not everyone in the rural area has a radio or the capacity to buy batteries, because there's no electricity in most areas," recalled KI14. "So, in rural areas, the government had to rely on local leaders, elders, women groups, tribal leaders, civil society groups. That challenge in communication in rural versus urban [areas] was addressed by having a centralized channel for disseminating messages with an incident management team in place deciding on the messages going out…There was a bottom-up and top-down approach mutually reinforcing the messaging."

Additionally, KI14 highlighted the role of the country's postwar peacebuilding infrastructure in supporting health communication, noting that it facilitated dialogue with chiefs in high-risk areas. KI14 also shared that targeted demand generation and awareness-building strategies helped increase vaccine uptake. These included establishing immunization sites in marketplaces, where women with children often worked or shopped; enlisting town criers; broadcasting UNICEF radio programming; and coordinating social media campaigns in support of immunization. KI11 corroborated these examples, sharing, “That was a major thing – building outreach into people’s schedules, linking to [community health workers, CHWs], which were introduced as a formal policy, and pairing with them to plan these outreach events.” On this point, the country’s National Community Health Services Policy – originally introduced in 2008, revised in 2011, and renewed in 2016 – established standards for community outreach, health promotion, and referral activities.[286] KI13 further underscored the importance of proactive health worker outreach to underserved populations with limited access to health facilities:

> “There’s a schedule of, say, every Monday I have to go to this location in my catchment community and vaccinate because people cannot come to the facility, because [their] child is not sick, or they have things to do, or they have many young children that cannot be left at home. There’s no motivation or incentive to walk for hours just to get vaccinated. So, it’s the vaccinator’s responsibility to make that trip, keep on schedule and get people vaccinated. One quarter of children in our system are vaccinated by that approach.”

In keeping with the recognition that both top-down and grassroots approaches were required to improve immunization coverage, Liberian officials also took steps toward strengthening post-epidemic health governance and sustaining political will around immunization. Liberia's President, Ellen Johnson Sirleaf, recognized the gravity of the epidemic early on and prioritized outbreak response efforts, describing Ebola as a threat to the country's "economic and social fabric."[287] Writing about Ebola in 2014, she also called for greater investment in Liberia's health infrastructure, referencing setbacks in routine immunization programming and predicting a resurgence of vaccine-preventable diseases.[288] A strong advocate for community health, Sirleaf also launched a national health assistance program to serve over 4,000 communities in the remotest parts of the country following the epidemic.[289]

The Liberian government further reified its commitments to routine immunization with key structural reforms and financial support. "Because [of] the introduction of yellow fever and pentavalent [vaccines], the Government of Liberia had to commit to co-finance the introduction of these two vaccines, and that has been sustained over the years," observed KI20. "The government has also demonstrated increased visibility of their support of the immunization program, as demonstrated by budgetary commitments annually to immunization and immunization products." In this vein, Liberia's Investment Plan articulated a strategy to formally ensconce IMS, Ebola-specific community health task forces, and other Ebola coordinating mechanisms within the country's health sector.[290] In this spirit, the government also strengthened referral mechanisms between Ebola treatment units and the rest of the country's health system, later developing a plan to decommission these units and transform them into permanent health facilities.[290]

Notably, the Liberian government also implemented a number of policy reforms to support post-epidemic recovery. For example, in a departure from the previously established donor-supported financial pooling mechanism for health, the Investment Plan also proposed establishing a government-led equity fund intended to "ensure financial risk protection, cushion against financial risks that limit access to care, and address systemic issues within existing provider payment mechanisms."[290] MoHSW also provided targeted technical assistance to counties with persistently low levels of coverage, high dropout rates, and poor supervisory reports – an approach dubbed "Parenting of Poorly Performing Counties."[291] Despite these positive developments, other key informants highlighted remaining shortcomings in leadership and tensions between competing approaches to health systems-strengthening: "The technical and political leadership in the health sector is a bit more challenged," asserted KI14. "You have a situation whereby the medical practitioners are inadequate to respond to the overall needs of the population. There is also a tension over where infrastructure should be provided, or health providers placed. That is also related to governance of health infrastructure."

Though efforts to rebuild Liberia's health system and improve routine immunization coverage following the Ebola epidemic achieved significant progress, several challenges remain. A 2017 data quality audit, for example, reported that data collected through IDSR was not being used to support subnational (i.e., facility-level) decision-making and prioritization; many facilities surveyed also reported poor Internet connectivity, electricity outages, and limited access to mobile phones and computers.[292] KI11 agreed that data management challenges complicated efforts to track vaccination activities, adding, “There was a lot of push data that was generally accurate. But the books didn’t let you easily figure out who was missing what…So, vaccinators had to go line by line to say, this kid is nine months old, circle his name, and now I have to go find him.” KI13 also described how Liberia’s weak population-level data collection capacities hamper efforts to measure immunization coverage and forecast vaccine demand:

> “We do not have a very effective population registry system.…The population is changing, but we use a growth rate that varies from time to time and is not the same across counties or communities because of population migration and other factors. It’s a big challenge to determine actual coverage since we’re using a denominator from 2008. Once we have a good birth registration system or a good health information system that is universal or tracking 98% or 95% of deliveries, then we can say, look, our estimate should be based on deaths under one and deliveries as the basis for our denominator. We have ten to fifteen percent of women delivering outside health facilities, though…If you do not know how many children are born or die, then you cannot make a good estimate. So, coverage is likely different than what actually comes out of national surveys. In African countries, we have to wait ten years to know our population and track our population movement.”

In addition to poor data quality, numerous immunization challenges identified in this study revolve around the management, training, and retention of Liberia's health workforce. Reflecting on workforce culture in Liberia following the Ebola epidemic, KI11 remarked, "[Health workers] were overworked and underpaid, so they had to work two jobs and try to be in two places at once. They were not prepared for what they faced every day…The people who work in the health system there try really hard and really care, too. They're incredibly resilient."

Late or missing payments for health workers was a recurrent theme, both among the key informants and in the literature. Gavi reported in 2017 that while some 1,110 health workers had been trained in immunization as part of the country's Ebola recovery efforts, Liberia's health sector still had only 795 working vaccinators, of whom only 25% were on the government's payroll. Furthermore, there was high attrition among health workers assigned to the southeastern region of the country due to difficult living and working conditions.[275] KI13 posited that weak vaccinator recruitment, training, and payment practices were partly responsible for these challenges, explaining:

> "We have a vaccinator cadre of HCWs – they are like nurse aides, but they haven't undergone formal training. They learn from mentoring, coaching, experience on the job; there's no formal schooling for immunization. They do in-service training. They get recruited because they are a nurse aide or they're working in a health facility. They're way down on the chain. They maybe have high school graduation or

> secondary. They're not university graduates [and] haven't gone through formal schooling to become HCWs…No one knows how they get paid. Sometimes they sacrifice for weeks or months, but you don't get on payroll for one, two, or three years and sometimes just on a part-time basis. Those who hire you are not involved in the payroll process. So, 10% of vaccinators are contractors – not on government payroll – and they're hired by [a] facility to be paid by NGOs. So once the project ends, they stay and hope they get on payroll."

As many as 41% of Liberia's public sector health workers went on strike during the Ebola epidemic to protest their exclusion from the government's payroll, prompting the World Bank, African Development Bank, and United Nations Development Programme to help subsidize hazard pay.[293] KI19 acknowledged that newer practices – such as UNICEF's mobile app, which sends payments directly to health workers instead of relying on the government to handle disbursement – were an improvement. However, they reported that payroll challenges still plagued community health workforces supporting immunization: "It is a serious challenge. We are heavily donor-driven. There is also some issue with transparency for funding by partners. UNICEF is providing funding to pay community health assistants while World Bank is providing funding, [so] why are these people not getting paid? When funders pull out, how are we going to find funding for them? The government has very scarce resources and we are not ready to pay community health assistants on the payroll."

3.5 CROSS-CASE ANALYSIS

3.5.1 Descriptive Statistics

Our one-way repeated measures ANOVA revealed several statistically significant differences between Haiti and Liberia in terms of the proportion of districts reporting 80% or higher coverage of MCV1 ($F[10, 9]$, $p = 0.0491$), domestic government health expenditure per capita ($F[10, 9]$, $p = 0.00$), and external health expenditures per capita ($F[10, 9]$, $p = 0.0007$) during the five years preceding and following their respective epidemics. However, there were no significant differences between Liberia and Haiti in terms of the proportion of districts reporting 80% or greater coverage of DTP3 or dropout rates between DTP3 and the MCV1. In Haiti, the average proportion of districts reporting greater than 80% MCV1 coverage decreased considerably in the five years following the onset of its cholera epidemic. This period also saw a slight decrease in average domestic government health spending and larger increases in average vaccination dropout rates and external health spending. Liberia reported a slightly lower average proportion of districts reporting greater than 80% MCV1 coverage in the five years following its Ebola epidemic, along with a slight decrease in average government health expenditures and a doubling of external health expenditures; notably, average dropout rates during this period also decreased (see Table 3).

Table 3. Pre- & Post-Epidemic Immunization Coverage & Health Spending in Haiti and Liberia											
Haiti						Liberia					
Year	**Proportion of Districts with ≥ 80% MCV1 Coverage (%)**	**Proportion of Districts with ≥ 80% DTP3 Coverage (%)**	**Dropout Rate Between DTP1 and MCV1 (%)**	**Domestic General Government Health Expenditure per Capita (PPP Int$)**	**External Health Expenditure per Capita (PPP Int$)**	**Year**	**Proportion of Districts with ≥ 80% MCV1 Coverage (%)**	**Proportion of Districts with ≥ 80% DTP3 Coverage (%)**	**Dropout Rate Between DTP1 and MCV1 (%)**	**Domestic General Government Health Expenditure per Capita (PPP Int$)**	**External Health Expenditure per Capita (PPP Int$)**
2005	23	-	-4	13	25	2009	73	87	5	35	10
2006	21	50	27	6	35	2010	80	47	15	33	8
2007	50	47	30	19	30	2011	53	53	17	32	16
2008	29	29	-	20	32	2012	40	93	22	42	10
2009	26	44	18	21	33	2013	20	87	24	48	5
2010	46	68	40	22	56	2014	7	13	22	46	11
2011	4	50	39	11	104	2015	27	20	17	44	15
2012	2	47	30	13	95	2016	53	80	19	41	19
2013	5	57	11	14	59	2017	33	87	12	35	21
2014	9	30	10	14	75	2018	47	93	8	26	26
2015	-	32	19	17	78	2019	87	87	10	-	-
Pre-Epidemic											
Mean (SD)	29.8 (11.7)	42.5 (9.3)	17.8 (15.4)	16 (6.1)	31 (3.9)	**Mean (SD)**	53.2 (24.4)	73.4 (21.6)	16.6 (7.4)	38 (6.8)	10 (4.2)
Post-Epidemic											
Mean (SD)	5 (1.6)	43.2 (11.7)	21.8 (12.5)	14 (2)	82 (17.6)	**Mean (SD)**	49.4 (23.5)	73.4 (40.2)	13.2 (4.7)	36 (8.2)	20 (4.5)

3.5.2 Stacked Case Analysis

Table 4 – which presents a matrix displaying the findings from each case stacked side-by-side, organized within the Essential Public Health Services framework – facilitates comparison between the post-epidemic recovery experiences of Liberia and Haiti by disaggregating findings across relevant domains of health system functioning (i.e., assessment, policy development, and assurance). Per the Framework, the assessment domain relates to routinely monitoring population health and investigating potential health hazards. Following their respective epidemics, both Haiti and Liberia adopted robust case-based approaches to surveilling vaccine-preventable diseases. In Liberia, however, the IDSR and EWARN systems – coupled with strong case reporting mechanisms, targeted assistance to underperforming counties, and community-based surveillance systems – contributed to better immunization outcomes long after the Ebola epidemic. Though Haiti established a national reference laboratory and developed an accompanying strategic plan, poor equipment availability and high maintenance costs threaten its fiscal sustainability.

The Framework's policy development domain encompasses effective communication and health education, community mobilization, policy formulation and implementation, and legal and regulatory measures to promote health. In Liberia, a combination of top-down and grassroots-level communication strategies – coupled with active outreach to last mile communities – played an important role in recouping losses in routine immunization coverage. However, efforts to socialize post-cholera routine immunization in Haiti floundered; poor patient experiences at health facilities further diminished public demand for immunization services. Despite strong relationships with external donors and international organizations, Haiti also struggled to mobilize partnerships with domestic civil society groups well-poised to promote immunization, such as the Haitian Red Cross. Like Haiti, Liberia also sustained strong relationships with international donors; additionally, it excelled at forging partnerships with community champions and civil society organizations, which proved consequential to improving post-Ebola immunization coverage. The two countries also differed considerably in terms of post-epidemic health system policy formulation. Numerous Liberian policies, strategic plans, and laws demonstrated strong alignment in their vision for a more resilient post-Ebola health system, and several included specific provisions for improving routine immunization. The majority of Haiti's post-cholera plans and policies, by contrast, did not mention immunization or explicitly articulate strategies for improving coverage beyond the Post-Disaster Vaccination Plan or the EPI program's cMYP.

The final domain of the Framework, assurance, addresses the importance of ensuring equitable access to needed services, supporting a diverse and skilled health workforce, sustaining a strong organizational infrastructure for public health, and strengthening public health functions through evaluation, research, and continuous quality improvement. Access to immunization services in Haiti was often impeded by violence, user fees, stockouts, long wait times, and weak referral mechanisms to primary care facilities. Parallel challenges were observed in other realms of public infrastructure in Haiti, where poor transportation and sanitation systems, weak cold chain capacities, and complex land ownership laws hindered efforts to establish permanent mechanisms for vaccine delivery. Though Liberia experienced similar infrastructural challenges, it still managed to strengthen referral mechanisms between

Ebola treatment units and primary care facilities, scale up EPHS delivery, and establish a National Public Health Institute to inform long-term health systems-strengthening activities.

Despite differing trajectories of post-epidemic immunization coverage, Haiti and Liberia share a critical weakness: health workforce dissatisfaction. Health workers in both countries – including vaccinators and community workers supporting routine immunization programs – were often unhappy with their training, compensation, and geographic placement. In both countries, the epidemic in question diverted health workers from routine service provision, including immunization. Additionally, difficult working conditions and more lucrative offers from donor-funded campaigns resulted in health worker attrition from the public sector. Moreover, despite strong microplanning capacities, both countries reported major challenges in data management, estimating immunization coverage, and forecasting vaccine demand. Left unresolved, these shared challenges will likely hinder efforts to achieve and sustain high levels of routine immunization coverage, as well as coordinate new vaccine introductions in the future.

Table 4. Matrix of Stacked Cases
Using the Essential Public Health Services Framework

Core Function	Essential Public Health Service	Immunization Program Recovery in Haiti	Immunization Program Recovery in Liberia
Assessment	Assess and monitor population health status, factors that influence health, and community needs and assets	▪ Active case-based, sentinel, and environmental surveillance for vaccine-preventable diseases ▪ Limited availability of equipment (e.g., computers)	▪ Adoption of IDSR & EWARN systems ▪ Strong reporting mechanisms for notifiable conditions ▪ Strong case- and community-based surveillance protocols
Assessment	Investigate, diagnose, and address health problems and hazards affecting the population	▪ Creation of a tiered, pyramidal network with a national reference laboratory ▪ Development of a strategic plan and regulatory/legal framework ▪ Funding from PEPFAR ▪ Equipment maintenance outsourced to contractors	▪ Adoption of IMS structure ▪ Creation of an emergency operations Center ▪ Targeted technical assistance provided to counties with poor immunization coverage
Policy Development	Communicate effectively to inform and educate people about health, factors that influence it, and how to improve it	▪ Lack of communication and messaging to raise awareness of the importance of vaccination ▪ Poor patient experiences at healthcare facilities	▪ Intensified communication efforts via top-down and bottom-up approaches ▪ Active outreach to communities without static clinics ▪ Marketplace-based outreach ▪ Radio programming
Policy Development	Strengthen, support, and mobilize communities and partnerships to improve health	▪ Strong relationships with international donors ▪ Lack of formal partnerships between the EPI program and civil society groups (e.g., Haitian Red Cross)	▪ Strong relationships with international donors ▪ Contracting with civil society organizations to support community engagement ▪ Coordination with tribal chiefs, elders, women groups, and other community champions ▪ Signatory to IHP+

Policy Development	Create, champion, and implement policies, plans, and laws that impact health	▪ cMYP 2011-2015 ▪ Dedicated National Post-Disaster Vaccination Plan ▪ PDNA and cholera elimination plans do not mention routine immunization	▪ Political prioritization of immunization ▪ National Health and Social Welfare Policy and Plan ▪ National EPI Strategic Plan ▪ Investment Plan for Rebuilding a Resilient Health System ▪ National Health and Social Welfare Policy & Plan ▪ National Community Health Services Policy ▪ Economic Stabilization and Recovery Plan ▪ National Action Plan for Health Security ▪ National Health and Social Welfare Financing Policy & Plan
Policy Development	Utilize legal and regulatory actions designed to improve and protect the public's health	▪ No national legislation on immunization ▪ Highly centralized organization of public sector health programs	▪ Public Health Law (2019) ▪ Improved accountability and partner coordination within a decentralized health system structure
Assurance	Assure an effective system that enables equitable access to the individual services and care needed to be healthy	▪ Lack of referral mechanisms between cholera treatment units & primary care ▪ Long distance to health facilities; long wait times; inaccessible transportation ▪ Gang violence ▪ Vaccine stockouts ▪ Fee-for-service scheme	▪ EPHS ▪ Referral mechanisms strengthened between Ebola treatment units and routine health facilities ▪ Urban Immunization Strategy ▪ Reaching Every District

Assurance	Build and support a diverse and skilled public health workforce	▪ Shortage of qualified primary health workers in the public sector ▪ Low, delayed compensation for public sector health workers ▪ Attrition of health workers from the public sector	▪ Increased immunization workforce training ▪ Expansion of Field Epidemiology Training Program efforts ▪ Low, delayed compensation for public sector health workers ▪ Health worker strikes ▪ Attrition of health workers from the public sector ▪ Need for health worker educational reforms
Assurance	Improve and innovate public health functions through ongoing evaluation, research, and continuous quality improvement	▪ Strong microplanning capacities ▪ Efforts made to learn from prior disasters in Africa & Asia ▪ Poor census data & unreliable coverage estimates ▪ Weak data management and data-sharing mechanisms	▪ Strong microplanning capacities ▪ Major improvements in infection prevention & control ▪ Implementation of quality improvement measures at health facilities ▪ Data discrepancies across parallel information systems ▪ Poor census data & unreliable coverage estimates
Assurance	Build and maintain a strong organizational infrastructure for public health	▪ Weak public infrastructure (roads, transportation, sanitation systems, energy, buildings, etc.) ▪ Weak cold chain capacities ▪ Few functional health facilities; reliance on temporary structures (e.g., tents) ▪ Land ownership challenges ▪ Parallel, donor-created information systems with no integration ▪ Insufficient staffing at health posts	▪ Transitioning Ebola treatment units into health facilities ▪ Improved staffing at facilities ▪ Major expansion of cold chain capacities ▪ Established a National Public Health Institute

In addition to the domains articulated in the Framework, we identified several other similarities and differences between the two cases relating to the roles of colonialism in shaping the health system environments of both countries, the importance of country ownership and autonomy in matters of health governance, and the role of integration in shaping cohesive approaches to post-epidemic recovery. We discuss these issues in greater detail below.

<u>3.5.3 Colonial Legacies</u>

Historical injustice is a powerful driver of contemporary inequity. Quoting Nobel laureate Amartya Sen, the infrastructure scientist Debbie Chachra writes, "'The usefulness of wealth lies in the things that it allows us to do—the substantive freedoms it helps us to achieve.' This is also a fairly good description of infrastructural systems: they're a general-purpose means of freeing up time, energy, and attention."[294] In this vein, centuries-long depletion of social, financial, and political capital initially paralyzed response and long-term recovery efforts in both Haiti and Liberia. And, as demonstrated in both cases, extractive colonialist practices – military occupation, extortion, distortion of national priorities, and undermining of political authority – have done significant harm to populations and health systems in Haiti and Liberia. The political theorist Peer Illner has also commented that "[disaster relief] has passed from the domain of state-led, paid reproductive work to the sphere of unwaged reproductive labour. This recent trend has been threefold: exposing communities to disaster by eroding their conditions of life through austerity; abandoning them to survive on their own; then selling off what remains of public relief infrastructures to commercial operators, once the immediate threat has receded."[295] Illner's observations mirror the colonial patterns of encroachment and extraction observed in both countries – commandeering aid flows, outsourcing or privatizing state capacities, and eschewing government autonomy in deference to donor preferences – which in turn were reified by international responses to the Ebola and cholera epidemics. The consequences of such practices impeded long-term recovery from these epidemics and efforts to resume routine immunization activities, particularly in Haiti.

3.5.4 Country Ownership and Autonomy

The political scientist Pavithra Suryanarayan writes, "Building state capacity in the short run is inordinately hard because an effective state requires a range of technical capabilities such as bureaucratic power, informational capacity, and coercive capacity."[296] As demonstrated in both countries but especially in Haiti, vertical, donor-driven health initiatives implemented in a vacuum of state capacity risks undermining public sector agency, credibility, and autonomy; creates an economy of overreliance on external aid to subsidize public goods, including common goods for health; undercuts public trust in a government's ability to fulfill its social contract; and, in some cases, does little in the long term to develop, operationalize, and institutionalize knowledge, expertise, and capital within the public sector.[297] On this note, Noor also writes, "You must accept that countries are sovereign entities, fully responsible for planning, resourcing, implementing and monitoring their national response. Your help is needed, your ideas are welcome but the solutions to country problems must be arrived at by countries themselves. Ethical partners know theirs is a supportive role."[298]

Both cases strongly underscore the importance of Noor's principles of ethical donor-country engagement. Though the literature and interviewees offered critiques of both Liberian and Haitian leadership and donor-driven health initiatives were prevalent in both countries, MoHSW appears to have secured a far greater degree of ownership and autonomy over Ebola response and health system recovery efforts than its MSPP counterparts following the cholera epidemic. By devising a plan to vest control of health financing within its own government and embedding Liberian leaders and experts within donor-funded response and recovery mechanisms, Liberia was able to rapidly scale up national immunization coverage while drastically reducing coverage inequities. The ethos of centering Liberian leadership and technical knowledge shaped nearly all aspects of response and recovery, from revitalizing IDSR and formulating the Investment Plan to implementing IMS and prioritizing community health. Political leaders' firm commitment to improving immunization and community health capacities – which, in turn, was underpinned by programmatic and financial support – was also instrumental in achieving this. By contrast, the sidelining of MSPP in Haiti and fragmentation of financial and decision-making power across a slew of external actors obstructed cohesive action around immunization. Furthermore, the absence of a unified government response to the cholera outbreak impeded priority-setting, policymaking, and budgeting activities required for long-term immunization program recovery.

3.5.5 Integration

From health system ownership and autonomy follows integration: the alignment of health system leaders, priorities, funding streams, policies, workforces, and external stakeholders across a full spectrum of coordinated, comprehensive health service provision.[299] The post-epidemic immunization model adopted in Liberia – wherein targeted campaigns were not the primary modes of vaccination, but rather supplemented EPHS delivery – resulted in greater coverage compared to Haiti, where standalone vaccination campaigns were implemented largely in isolation from other primary health services and providers. Furthermore, Liberia achieved clear alignment across the various plans, policies, priorities, and budgets guiding immunization program recovery following Ebola. By contrast, limited planning and budgeting capacities in Haiti, the omission of routine immunization from key strategic plans, and the predominance of external decision-makers and consultants in decision-making around health indicate a less-integrated approach to improving equitable immunization coverage after the cholera epidemic.

3.6 DISCUSSION

This investigation examined the factors contributing to equitable post-epidemic routine immunization coverage in Liberia and Haiti. Lessons learned from past emergencies – infectious disease outbreaks, natural disasters, manmade catastrophes, and others – suggest that health systems should ideally possess the ability to scale up robust horizontal capacities for routine service provision to meet the demands of emergent crises.[300] Yet, the divergent trajectories of post-epidemic routine immunization program recovery in these countries illustrate how such logic often fails in resource-constrained settings, where baseline health system capacities may be weak or missing altogether. We found that achieving strong alignment between immunization policies, integrating routine immunization into robust systems of primary care, and respecting country ownership and autonomy over health system functioning were essential to improving equitable immunization coverage in Liberia. By contrast, the absence of these factors may have contributed to widening coverage disparities in Haiti.

While the specific approaches adopted in these countries may not be universally applicable in every low- or middle-income setting, or after every type of infectious disease outbreak, this study did generate important insights about the facilitators and deterrents of routine immunization program recovery following major epidemics. These insights, in turn, may be transferrable to other resource-constrained settings characterized by weak primary care systems, a heavy reliance on external aid to subsidize both routine and emergency health system activities, and a strong donor presence. Political leaders and domestic health authorities in affected countries should conduct long-term planning to ensure alignment between budgets, plans, and routine immunization programs; treat routine immunization and community health systems as critical national priorities worthy of sustained, long-term investment; strengthen linkages between various health system components; and improve compensation structures and working conditions for public-sector health workforces. Donors and other external stakeholders, meanwhile, should strive to embed local expertise and leadership within vertical response and recovery structures, promote country ownership of domestic health programs, and work with in-country political leaders to support long-term budgetary and policy planning around routine immunization, community health, and primary care.

This investigation does have some limitations. First, none of the investigators speak, read, or write French, Haitian Creole, or any non-English language spoken in either Haiti or Liberia with enough proficiency to analyze relevant documents produced in these languages. Similarly, we were unable to interview key informants unless they could converse in English. A second limitation relates to the types of key informants recruited for this study: nearly every interviewee we consulted about Haiti was or is currently affiliated with donor agencies that responded to the earthquake and cholera epidemic. However, we were unable to secure many interviews with individuals affiliated with MSPP or Haitian-led organizations. Conversely, the majority of informants interviewed about Liberia were of Liberian descent and either currently or formerly affiliated with public-sector institutions that responded to the Ebola epidemic, while few represented donor agencies or external partners. As a result, our findings for both countries do not account for demand-side or end-user (i.e., patients, communities) perspectives on immunization program recovery, and in the case of Haiti, they do not sufficiently reflect public-sector perspectives (e.g., from MSPP). Furthermore, we identified very few peer-reviewed studies and grey literature documents featuring Haitian authorship; MoHSW authors, by contrast, were comparatively well-represented in published scholarship on Ebola, routine immunization, and post-epidemic recovery. Given these omissions and the aforementioned language barriers, it is likely that valuable perspectives on immunization and health system recovery are missing from both cases – particularly Haitian perspectives.

The Essential Public Health Services framework was an intuitive tool in terms of articulating a set of basic organizing principles for health systems and providing a common vernacular for discussing recovery across diverse health system stakeholders. However, it also has some limitations, which became apparent over the course of this investigation. First, the Framework appears to be conceptual in design rather than analytical; as such, it does not indicate how individual essential services should be weighted relative to one another, nor does it suggest how they should be organized, the time required to establish said services, or the order in which stakeholders should pursue them. Furthermore, as Fitter et al. note in their analysis of public health system recovery in Haiti, the Framework does not explicitly account for health governance, political will, leadership, or financing.[185] Perhaps these were envisioned as cross-cutting competencies or considerations rather than essential “services”; if so, a clearer statement of the assumptions underpinning the Framework would be valuable.

Accompanying Framework guidance states, “To achieve equity, the Essential Public Health Services actively promote policies, systems, and overall community conditions that enable optimal health for all and seek to remove systemic and structural barriers that have resulted in health inequities.” The Framework positions equity as the core of the ten essential services but makes no mention of ethics or justice beyond this stated purpose. Nevertheless, by deeming certain services “essential,” the Framework makes implicit normative judgements about their value without explicitly considering structural factors – such as state capacities and colonial legacies – that shape their availability, provision, and utilization. Finally, the Framework does not clearly explicate linkages between individual essential services. Mounier-Jack et al. present similar critiques of WHO’s health system building blocks model – which, like the Framework, does not account for demand-side considerations associated with health service provision or structures of power and decision-making.[301] Thus, practitioners and policymakers might consult the Framework to arrive at a common understanding of health system needs and priorities following a major crisis, but may find it less useful as an operational tool for guiding health system recovery efforts. In the context of this investigation, these limitations may have impeded more granular comparisons between the leadership dynamics, financing schemes, and broader social, political, and environmental factors contributing to each country's post-epidemic trajectory.

To assess the confirmability of this investigation, follow-on case studies might examine post-epidemic immunization programs in other settings to determine whether similar barriers and facilitators of recovery exist. Coupling other methodological frameworks, such as a positive deviance lens, with additional forms of data (e.g., social media content, financial data, mobile data) and modes of data collection (e.g., focus groups, community-based participatory research, surveys) could also yield rich insights into demand-side considerations for post-epidemic health system recovery.[302] Future analyses might also compare and contrast perspectives across sectors and stakeholders (e.g., donors, NGOs, public-sector health institutions, patients) to paint a more comprehensive picture of post-epidemic recovery. Additionally, a formal power analysis of post-epidemic health system reforms could elucidate how relationships between donors, policymakers, practitioners, and communities shape population health outcomes following major crises.[303]

As the world continues to combat COVID-19, these findings may be especially salient for health practitioners working to reverse population health setbacks and ensure the continuity of core public health programs like routine immunization. For example, donors might consider earmarking a portion of COVID-19 emergency response funds toward ensuring the continuity of routine immunization programs and integrating COVID-19 vaccination capacities into primary care systems, while ministerial and subnational health officials should explicitly account for these considerations in pandemic response and recovery plans. Decision-makers in LMICs – as well as donors supporting health programs in these settings – will play particularly important roles in course-correcting health systems struggling to meet the demands of the pandemic, often at the expense of providing core primary health services. How these stakeholders coordinate both intra- and post-pandemic recovery efforts will shape future trajectories of population health and health equity.

AIM THREE

Group-Based Trajectory Models of Integrated Vaccine Delivery and Equity in Low- and Middle-Income Countries

"The final and perhaps most fundamental question is how to ensure true equity in reaching those in greatest need. This goes well beyond issues of equal coverage. Rather than traditional bureaucratic concerns about equalizing input, a more cost-effective approach may be to focus on outcome. This will require means to identify those in greatest need and at most risk. A new approach to surveillance may be needed to evolve social indicators to monitor pockets where health problems are concentrated. Public funds can then be focused where they will make the greatest difference in improving the health of the community. But the political ramifications of such an egalitarian approach to affirmative action are manifestly complex."

Carl Taylor and Richard Jolly

"The Straw Men of Primary Health Care"

4.1 ABSTRACT

Integrated vaccine delivery – the linkage of routine vaccination with provision of other essential health services – is a hallmark of robust primary care systems that has been anecdotally linked to equitable improvements in population health outcomes. In this investigation, we gather longitudinal data relating to routine immunization coverage

and vaccination equity in 78 low- and middle-income countries that have ever received support from Gavi, the Vaccine Alliance, using multiple imputation to handle missing values. We then estimate several group-based trajectory models to describe the relationship between integrated vaccine delivery and vaccination equity in these countries. We identified five distinct trajectories of geographic vaccination equity across both the imputed and non-imputed datasets, along with two and four trajectories of socioeconomic vaccination equity in the imputed and non-imputed datasets, respectively. We find that integrated vaccine delivery is most strongly associated with improvements in vaccination equity in settings characterized by high baseline levels of inequity. We also address critical challenges in measuring both integration and equity and call for continued scholarship further characterize the relationship the two.

4.2 BACKGROUND

Health systems research in low- and middle-income settings features a longstanding debate over the merits of vertical versus horizontal modes of health service delivery. Broadly, vertical programs are disease-specific, often freestanding initiatives with specified objectives to be achieved within a limited timeframe.[13] The Global Polio Eradication Initiative – a USD$20 billion program that has eliminated poliomyelitis incidence by 99.9% since its inception in 1988 – is a classic example of a vertical health program, as is the ongoing global COVID-19 vaccination effort.[39] By contrast, the World Health Organization (WHO) defines horizontal (i.e., “integrated”) approaches as “the process of bringing together common functions within and between organizations to solve common problems, developing a commitment to shared vision and goals and using common technologies and resources to achieve these goals."[304] Systems for delivering comprehensive primary health care – including all preventive, curative, palliative, and rehabilitative services needed over a person's lifetime – embody the ethos of integrated health service provision.[305] Finally, some initiatives elect to adopt hybridized approaches: the Expanded Programme on Immunization (EPI), for example, is a primary care program that focuses on cost-effective, vertical delivery of routine health services, while Integrated Management of Childhood Illness is a widely adopted health package that not only targets childhood diseases, but also aims to strengthen health workers' case management skills, encourage positive care-seeking behaviors among patients, and promote preventive care.[13]

The widespread prevalence of vertical programs across the global health landscape raises questions about conditions under which it is appropriate to transition a given vertical program into an integrated, horizontal system – and, if appropriate, how best to facilitate this transition. A robust body of literature affirms the value of pursuing integrated approaches to delivering many routine health services, citing potential improvements in health system governance, program sustainability, community involvement, equitable provision of care, and access to and coverage of essential services.[306–310] Other analyses paint a murkier picture: several systematic reviews, for example, assert that the purported benefits of integration are highly variable across contexts or remain largely unproven in public health and healthcare practice, and cite logistical challenges, unequal resource allocation, and limited immunization capacities as barriers to achieving desired levels of coverage.[311–314]

Though integrated delivery may not be suitable for every health service, a substantial body of evidence affirms the value of integrated routine vaccine delivery. In fact, WHO identifies integrated delivery as an important strategy for increasing routine vaccination coverage.[17] Because immunization coverage is relatively high in many countries, vaccination programs are an attractive vehicle for concomitantly increasing coverage of other critical health services. For this reason, WHO's Global Vaccine Action Plan 2011-2020 includes integration as one of its six guiding principles, underscoring its role in achieving immunization coverage goals and providing a platform for other public health interventions, such as Vitamin A supplementation and deworming.[18] Additionally, a study by Niessen et al. found that expanded vaccine coverage – coupled with nutritional programs and indoor air pollution control measures – could reduce pneumonia-associated child mortality by as much as 13-17% in the 40 countries with the highest mortality.[315] Similarly, a systematic review of the economic benefits of vaccination reports that using vaccines in conjunction with other treatments and community infrastructure-strengthening efforts actually improves the financial sustainability and affordability of healthcare programs in low- and middle-income countries (LMICs).[19] WHO notes that "integrated health services by design enhance equity; they encourage the selection of services based on the holistic needs of a given population and deliver many different types of care across the life course, from health protection and promotion and disease prevention to diagnosis, treatment, disease management, long-term care, rehabilitation and palliative care. This continuum of care is coordinated across the different levels and sites of care within and beyond the health sector."[299] For the purposes of this investigation, we extrapolate from this description to define ***integrated vaccine delivery*** as the linkage of routine vaccination services with other core public health interventions within a primary healthcare system.

Some evidence suggests that linking immunization with other public health interventions (e.g., deworming, Vitamin A supplementation, bednet distribution) can help reduce vaccination inequities in LMICs.[316–319] The United Nations Development Programme writes, “vaccine equity means that vaccines should be allocated across all countries based on needs and regardless of their economic status. Access to and allocation of vaccines should be based on principles grounded in the right of every human to enjoy the highest attainable standard of health without distinction of race, religion, political belief, economic, or any other social condition.”[320] In this vein, a study by Gupta et al. reports that implementation of India’s National Rural Health Mission – which aims to integrate management of childhood and neonatal illnesses – led to significant reductions in vaccination coverage disparities between urban and rural populations, wealthy and poor populations, and male and female children.[20] Similarly, in Madagascar, integrating insecticide-treated bednet delivery with measles immunization efforts has been found to increase measles vaccination coverage among the hardest-to-reach children. Various studies also advocate for integrating routine immunization with other core services as an effective strategy for reducing inequities in health service coverage.[21] For example, countries receiving financial and programmatic support from Gavi, the Vaccine Alliance (“Gavi,” a public-private partnership dedicated to increasing immunization access in poor countries) have implemented strategies aimed at improving health equity and strengthening health systems.[321] Despite the documented benefits of integrated vaccine delivery, its relationship with vaccination equity has not, to our knowledge, been systematically studied across LMICs. Moreover, we have not identified any studies measuring the longitudinal impacts of integrated vaccine delivery on vaccination equity at the country level.

Here, we examine *the relationship between* ***integrated vaccine delivery*** *and* ***vaccination equity*** *in low- and middle-income countries* by using longitudinal data to develop several group-based trajectory models. This investigation commences with an overview of measurement and data collection activities, followed by a description of the method and analytical procedures; results from the analysis; and a discussion of the findings, limitations of this investigation, and potential directions for future research in this area.

As it did not qualify as human subjects research, this investigation was deemed exempt from full review by the Institutional Review Board at the Johns Hopkins Bloomberg School of Public Health (FWA #00000287).

4.2.1 Measuring Integrated Vaccine Delivery & Vaccination Equity

First, we purposively examined the peer-reviewed and grey literature for existing measures of vaccination equity and health system integration. We found that studies of vaccination distribution and uptake in LMICs generally frame equity in terms of crude coverage within and across key dimensions of vulnerability, including but not limited to age, sex or gender, race, wealth level, education level, citizenship status, and geography (i.e., urban vs. rural setting).[322–327] Crude coverage refers to the proportion of individuals within a population targeted for vaccination that actually receives said vaccination (by contrast with effective coverage, which describes the proportion of a target population that receives a given vaccination and subsequently undergoes seroconversion, thereby developing protective immunity).[328]

The crude coverage-based approach to measuring vaccination equity has been embraced by many public health practitioners, donors, and decision-makers, including Gavi. As part of its 2016-2020 strategy to support equitable immunization programs in lower-income countries, Gavi published a set of accompanying indicators to monitor progress toward its stated vaccine, systems, sustainability, and market-shaping goals.[329] Two equity measures described in the strategy include equity of vaccination coverage by geography (i.e., the proportion of districts with coverage of the third dose of diphtheria-pertussis-tetanus-containing vaccine [DTP3] ≥80%, across all Gavi countries, hereinafter referred to as “geographic equity”) and equity of coverage by poverty status (i.e., the difference in coverage of the third dose of pentavalent vaccine between the richest and poorest quintiles, hereinafter referred to as “socioeconomic equity”).[329]

Arsenault et al. note that measuring absolute and relative coverage gaps between the wealthiest and poorest quintiles – the difference in coverage and the ratio of coverage, respectively – is an intuitive approach to quantifying vaccination equity when only two subgroups of analysis are under consideration (e.g., urban vs. rural, male vs. female).[330] However, applying this approach to poverty status could conceal disparities in coverage within and between mid-range wealth quintiles.[330] For this reason, we modified Gavi’s measures of geographic and socioeconomic equity to examine, respectively, the proportion of districts within a given country to achieve ≥80% crude coverage of the first dose of measles-containing vaccine (MCV1) and the slope index of inequality (SII). WHO defines SII as “a complex, weighted measure of inequality that represents the absolute difference in estimated values of a health indicator between the most-advantaged and most disadvantaged (or vice versa for adverse health outcome indicators), while taking into consideration all the other subgroups."[331] In this analysis, we calculated SII from estimates of MCV1 coverage disaggregated by wealth quintile. Larger, positive SII values indicate that high MCV1 coverage is more prevalent among wealthier quintiles, while smaller, negative values reflect greater coverage in poorer quintiles.

We chose to frame equity in terms of MCV1 rather than DTP3 or pentavalent vaccination coverage for several reasons. First, DTP doses are administered almost exclusively through routine health programs, whereas measles immunization efforts are often implemented through both horizontal and vertical pathways, even in settings with high MCV1 coverage.[332] As such, MCV1 coverage may be a more sensitive metric of integrated vaccine delivery. Second, in many countries, the first three doses of DTP vaccines are typically administered at two, four, and six months of life, respectively (or at 6 weeks, 10 weeks, and 14 weeks of life if using the pentavalent vaccine).[333,334] MCV1, however, is not administered until at least 9 months of life to prevent maternal antibody interference with the live vaccine and subsequent vaccination failure.[335] Due to patient attrition often observed between doses in resource-constrained settings, achieving and sustaining high MCV1 coverage thus represents a stretch goal for health systems in LMICs.[336,337] Furthermore, measles outbreaks function as proverbial "canaries in a coalmine," signaling poor health system functioning, persistent inequities in coverage, and challenges in immunization program implementation.[68,336,338–340] Finally, measles is among the most contagious diseases, infecting and killing tens of thousands of children each year and leaving survivors with permanently weakened immune systems.[341,342] Thus, we felt that equity measures framed in terms of MCV1 coverage would serve as more meaningful indicators of health system functioning and population health in LMICs.

In addition to the aforementioned metrics of vaccination equity, Gavi also utilizes a measure of integrated vaccine delivery developed by WHO's SAGE Decade of Vaccines Working Group ("the Working Group") – the only such measure that we identified in the literature and adopted in this analysis. This measure examines crude coverage of four core health services: DTP3, MCV1, protection at birth against neonatal tetanus (PAB), and at least one antenatal care visit (ANC1). If national co-coverage levels of these services are within ten percentage points of one another, and all four are at or above 70%, then the country in question is considered to have achieved integrated vaccine delivery as part of a robust horizontal health system. Per the Working Group, weak coverage correlation between these four services indicates poor integration, while the 70% threshold excludes weak health systems with poor service coverage across the board from being considered integrated.[329]

4.3 METHODS

4.3.1 Data Collection

From our purposive review of the literature, we identified several studies by Arsenault et al. that identified country-level predictors of vaccination equity in countries supported by Gavi.[330,343,344] Drawing from these studies, we determined which variables to gather for our investigation and designed a tool in Google Forms to collate data.

Next, we used the collation tool to compile a dataset of country-level indicators relating to routine health service coverage, socioeconomic conditions, and additional measures of health system performance for 78 countries that had ever received Gavi support, focusing on the years 2003-2019 (i.e., the period for which longitudinal routine immunization data from WHO were available).[†††] These measures were sourced from a broad range of publicly available repositories and sources, including the WHO-UNICEF Joint Reporting Forms on Immunization, WHO's Global Health Observatory and Global Health Expenditure Database, the Demographic and Health Surveys (DHS) Program, Multiple Indicator Cluster Surveys (MICS), and World Bank Open Data, among others. A complete summary of collected indicators and their sources is available in Appendix D.

4.3.2 Group-Based Trajectory Modeling

We performed group-based trajectory modeling (GBTM) to describe developmental trajectories of geographic and socioeconomic vaccination equity in Gavi countries between 2003 and 2019. GBTM was pioneered by Daniel S. Nagin and Kenneth C. Land, who first described the method in a landmark paper examining the relationships between age, rates of criminality, and differences between chronic and less-active criminal offenders.[345] GBTM has since been applied across a wide range of studies in psychology, sociology, criminology, and medicine.[346–349]

[†††] We excluded data from 2020 to avoid confounding effects on vaccine delivery due to the COVID-19 pandemic. We also excluded years preceding 2008 in our geographic equity analysis due to questionable district-level coverage estimates reported during those years.

GBTM is a method for approximating distinct developmental trajectories of an outcome of interest, drawing from longitudinal data. It has been described as a form of latent class modeling, wherein a set of observed variables are related to a set of latent variables (i.e., variables that are not directly observed, but inferred from observed variables).[350] Likewise, Nagin defines group-based trajectory models as specialized cases of finite mixture models, which assume the presence of unobserved latent classes in a population:

> "Many of the most interesting and challenging problems in longitudinal analysis have a qualitative dimension that allows for the possibility that there are meaningful subgroups within a population that follow distinctive developmental trajectories that are not identifiable ex ante based on some measured set of individual characteristics (e.g., gender or socioeconomic status)…For research problems with a taxonomic dimension, the aim is to chart out the distinctive trajectories, to understand what factors account for their distinctiveness and to test whether individuals following the different trajectories also respond differently to a treatment, such as a medical intervention, or a major life event."

GBTM is thus a technique for using longitudinal data to identify clusters of individuals who follow similar developmental trajectories, as opposed to forecasting the outcome of any individual group member. While it is possible to measure whether non-latent individual characteristics (i.e., predictors) are associated with a given outcome's trajectory, Nagin emphasizes that it is impossible to assign an individual preemptively or definitively to a specific trajectory; it is only possible to construct an expected trajectory. Furthermore, trajectories themselves are not immutable and are likely to evolve as additional data become available, or as individual subjects experience unmeasured life events or interventions.[351]

In a further departure from standard approaches to growth curve modeling like hierarchical modeling and latent curve analysis – which assume that trajectory parameters are continuously distributed throughout the population per a multivariate normal distribution – GBTM postulates the existence of distinct clusters or groupings of developmental trajectories of analytic significance, and assumes that individual trajectory differences can be summarized by a finite set of polynomial functions of time.[351] In other words, as Nagin writes, "The group-based method focuses on identification of different trajectory shapes and on examining how the prevalence of the shape and the shape itself relate to predictors. By contrast, standard growth curve modeling focuses on the population mean trajectory and how individual variation about that mean relates to predictors."[351] Thus, GBTM is a particularly useful method for characterizing distinct longitudinal trends in a given outcome of interest, as well as for describing phenomena like vaccination equity that may not follow a predictable developmental trajectory.

Though groups themselves are latent longitudinal strata and are not directly observable, they nevertheless have important conceptual and analytical value and can identify important longitudinal features of the dataset in question.[352] For example, identifying proportions of each group with risk variables of interest could reveal important insights into disease onset and progression. Adding risk factors or time-varying covariates to group-based trajectory models can also help assess the effects of major events on developmental trajectories within groups; conversely, treating group membership as a dependent variable allows researchers to control for complex developmental trajectories.[353] Finally, grouping allows for complex longitudinal data to be intuitively summarized, and can, according to Nagin, "provide a statistical snapshot of the distinguishing characteristics and behaviors of individuals following distinctive developmental pathways."[352]

To the best of our knowledge, GBTM has not been previously applied in peer-reviewed health systems research focusing on vaccination or LMICs, though the method has been used to examine country-level phenomena such as infant mortality and terrorism.[354,355] Given the methodological challenges associated with conducting health systems research at the country level, we posit that GBTM could serve as a useful tool for characterizing longitudinal trends in health system evolution. English et al. note, for example, that randomized controlled trials – generally considered to be the "gold standard" study design for ascertaining impact and causality – are often infeasible in health systems research due to the limited availability of randomizable units, the inherent complexities and heterogeneity of health systems and health interventions, the complexity of causal pathways, and the risk of contamination.[356] Methods like GBTM could help chart the developmental trajectories of health system performance over time, thereby elucidating how health outcomes of interest (e.g., equitable vaccination coverage) evolve longitudinally. This method could also help identify correlates of equity and facilitate comparison between high- and low-performing groups.

4.3.3 Using GBTM to Examine Integration and Equity

As a form of latent class analysis, GBTM lends itself to analyzing the relationship between integrated vaccine delivery and equity for several reasons. First, observable variables – such as immunization coverage, wealth, and population – are often prone to measurement error and method variance (e.g., when two methods of coverage estimation applied in the same setting produce differing estimates of coverage). By contrast, as Salkind writes,

> "Latent variable methodologies provide a means of extracting a relatively pure measure of a construct from observed variables, one that is uncontaminated by measurement error and method variance. The basic idea is to capture the common or shared variance among multiple observable variables or indicators of a construct. Because measurement error is by definition unique variance, it is not captured in the latent variable…When the observed indicators represent multiple methods, the latent variables also can be measured relatively free of method variance."[357]

Second, given significant heterogeneity within countries and the fact that countries develop and achieve equitable health outcomes at differing rates, classifying them based solely on observable characteristics measured at the national level may not adequately explain longitudinal trends in equity. For example, though income level is strongly associated with vaccination equity in LMICs, some countries (e.g., Nigeria, a lower-middle-income country) nevertheless report significantly lower levels of MCV1 coverage across wealth quintiles compared to their peers (e.g., Zambia, another lower-middle-income country) and in some cases, even their poorer counterparts (e.g., Malawi, a low-income country).[254,358] Thus, examining membership in unobserved classes may offer another approach to elucidating unexpected patterns in vaccination equity and relating these patterns to observable variables.[359]

Finally, both integration and equity manifest heterogeneously across countries. In the context of vaccination, for example, Sodha and Dietz note that infrastructural improvements may initially spark rapid increases in vaccination coverage, but these increases often plateau once coverage surpasses 80%.[360] As previously described, health service integration is also a highly dynamic phenomenon that may have varying effects on equity in different LMICs. In fact, WHO identifies six distinct uses of the term "integration": (1) deploying a package of preventive and curative health interventions for a particular population group; (2) establishing multi-purpose service delivery points (e.g., multi-purpose clinics); (3) ensuring continuity of care over time (either for chronic conditions or via a life cycle approach); (4) achieving vertical integration of different levels of service (e.g., referrals and shared health information across and between different levels of health service provision); (5) integrating policymaking, planning, and management (e.g., through shared supply chains); and (6) working across sectors to achieve desired health outcomes.[361] Wallace et al. further report that integrated provision of routine services (e.g., via Child Health Weeks) is typically more effective in settings with weak health systems, while Atun et al. highlight the role of local contexts in modulating the outcomes of integrated service delivery.[312,313] Thus, given the possibility of diminishing equity returns in settings with already-high coverage and the heterogeneous effects associated with different forms of health service integration, grouping countries by their respective developmental equity trajectories may serve as a useful comparative device.

4.3.4 Model Specification, Diagnostics, and Data Analysis

All data analysis was performed using Stata 17.[191] We used *traj*, a Stata plugin developed by Bobby Jones and Daniel Nagin, to estimate several group-based trajectory models of geographic and socioeconomic vaccination equity across the 78 countries in our sample.[362] We also used *siilin*, a command developed by the International Center for Equity in Health (Universidade Federal de Pelotas), to estimate SII for countries with publicly available MCV1 coverage estimates disaggregated by wealth quintile.[363] Accompanying Stata code for each analysis is provided in Appendices E-H.

We first performed multivariate normal imputation to handle missing data in our sample, given a high degree of missingness in the variables required to measure integration (i.e., ANC1 and PAB), as well as those required to measure our equity outcomes (i.e., geographic equity, SII, and MCV1 coverage across each of the five wealth quintiles). We performed 10 imputations across these 9 variables for all 78 countries. This created an imputed dataset of 14,586 observations, of which 2,140 were ultimately used in the imputation regression model (see Table 5 for a summary of dropped observations). The analyses described hereinafter were conducted separately on both the imputed and non-imputed datasets.

Next, we specified censored normal distribution models for each outcome of interest – geographic and socioeconomic vaccination equity – given that they are continuous (versus dichotomous or categorical) measures with discrete minimum and maximum values. We then determined the optimal number of trajectory groups to include in each model: holding all other parameters constant, we estimated models with two, three, four, and five groups and found that a five-group model produced high Bayesian information criterion (BIC) and entropy values for the geographic equity model, while four-group and two-group specifications proved optimal for the non-imputed and imputed socioeconomic equity models, respectively. Using procedures described by Soper, Cohen, and Westland, we estimated that a minimum of 1,599 observations would be required for the five-group geographic equity model to detect a small association (0.1) between integration and equity at 80% statistical power (p = 0.05), 150 observations to detect a medium association (0.3), and 38 observations to detect a large association (0.5). To achieve the same level of statistical power, the four-group socioeconomic equity model would require 1,454 observations to detect small associations, 137 observations to detect medium associations, and 34 observations to detect large associations.[364–366] The two-group socioeconomic equity model would require 947, 90, and 23 observations to detect small, medium, and large associations, respectively. Despite our small sample, we felt the large number of observations across countries would sufficiently power our analysis to at least detect large associations over the study period.

To determine whether equity trajectories depend on integration in addition to time, we included integration as a time-varying covariate in both models. We then toggled the polynomial order of the imp five-group geographic equity model and found that a linear specification for all groups produced high BIC and entropy values. A combination of intercept and linear polynomials produced a robust, non-imputed, four-group socioeconomic equity model, while linear polynomials alone proved sufficient in the imputed, two-group socioeconomic equity model. We used parametric bootstrap sampling to estimate group size confidence intervals. Next, we performed several of Nagin's recommended diagnostic checks for each model: calculating average posterior probabilities of group assignment, determining the odds of correct group classification, and conducting a visual inspection of confidence intervals in resultant trajectory plots (Table 6).[351] Finally, we performed multinomial logistic regression to identify predictors of group membership.

4.4 RESULTS

4.4.1 Country Characteristics

Our sample consisted of 78 low- and middle-income countries that have ever received Gavi support. The majority of the countries in the sample reside in sub-Saharan Africa (n = 40, 51.3%), per the World Bank's regional classification scheme, while 12 countries reside in East Asia and the Pacific (15.4%), 11 in Europe and Central

Asia (14.1%), 6 in Latin America and the Caribbean (7.7%), 2 in the Middle East and North Africa (2.6%), and 7 in South Asia (9%). Additionally, the World Bank classifies 28 countries (35.9%) in the sample as low-income, 40 (51.3%) as lower-middle-income, and 10 (12.8%) as upper-middle-income. Across both the imputed and non-imputed datasets, mean geographic and socioeconomic equity were highest in Europe & Central Asia and lowest in sub-Saharan Africa. Furthermore, upper-middle-income countries reported the highest mean levels of equity across both datasets, while low-income countries reported the lowest mean levels. Complete demographic details for the countries, along with mean geographic and socioeconomic equity measures disaggregated by region and income level, are summarized in Table 7.

4.4.2 Integrated Vaccine Delivery

Countries reported varying levels of integrated vaccine delivery (hereinafter referred to as "integration") over the course of the study period. Among low-income countries, 11 (out of 28 total, 39.3%) achieved integration of all four core services at various points between 2003 and 2019, compared to 20 (50%) lower-middle-income countries and 1 (10%) upper-middle-income country. Integrated vaccine delivery also varied geographically: 5 countries in East Asia and the Pacific (41.7% of all countries in the region), 3 (50%) countries in Latin America and the Caribbean, 5 (55.6%) countries in South Asia, and 19 (47.5%) countries in sub-Saharan Africa achieved integration at least once during the study period. By contrast, there were 78 countries (28 low-income, 40 lower-middle-income, and 10 high-income) that never achieved integration during the study period. The majority of these countries reside in sub-Saharan Africa (*n* = 21), followed by Europe and Central Asia (*n* = 11), East Asia and the Pacific (*n* = 7), Latin America and the Caribbean (*n* = 3), the Middle East and North Africa (*n* = 2), and South Asia (*n* = 2). Table 8 summarizes integration scores earned by each country during the study period.

4.4.3 Trajectory Analysis

Tables 9 and 10 present the maximum likelihood estimates for each model's parameters, Tables 11 and 12 display the confidence intervals for each model's equity estimates, Table 13 lists countries by group assignment, Tables 14 and 15 describe predictors of group membership, and Figures 10-13 illustrate the trajectories of geographic and socioeconomic equity over time. The geographic equity model produced five distinct trajectories across both the imputed and non-imputed datasets: a "low-increasing" curve (Group 1, blue), a "middle-decreasing" curve (Group 2, red), a "middle-stable" curve (Group 3, dark green), a "high-stable" curve (Group 4, orange), and a "middle-increasing" curve (Group 5, light green). In the non-imputed dataset, Groups 1-5 included roughly 13%, 18%, 27%, 30%, and 13% of the countries in our sample, respectively. The model based on the imputed dataset assigned 12%, 17%, 26%, 28%, and 16% of the countries to Groups 1-5, respectively.

The non-imputed socioeconomic equity model produced four distinct trajectories: a "low-inequity" curve (Group 1, blue), a "medium-decreasing" curve (Group 2, red), a "medium-stable" curve (Group 3, green), and a "high-inequity" curve (Group 4, orange). Groups 1-4 included roughly 39%, 30%, 27%, and 4% of the countries in our sample, respectively. By contrast, the imputed model produced two trajectories: a "low-stable" curve (Group 1, blue) consisting of 69% of countries in the sample, and a “high-stable” curve (Group 2, red) that included 31% of countries.

We did not detect a statistically significant association between integrated vaccine delivery and geographic equity using the non-imputed dataset, or in Groups 1-3 in the non-imputed socioeconomic equity model. However, there was a significant association between the two in countries belonging to Group 4 in the non-imputed socioeconomic equity model, both groups in the imputed socioeconomic equity model, and Groups 1-4 in the imputed geographic equity model. In the non-imputed dataset, integration was associated with a 0.53-unit reduction in SII in Group 4 (high-inequity). In Groups 1-4 in the imputed dataset, it was associated with 8.3-, 7.9-, 4.6-, and 1.6-percentage point increases per one-unit change in integration score, respectively, in the proportion of districts reporting greater than 80% MCV1 coverage. In this same dataset, integration was associated with a 0.054-unit reduction in SII in Group 1 (low-stable) countries and a 0.12-unit reduction in SII in Group 2 (high-stable) countries.

4.4.4 Predictors of Group Membership

Tables 15 and 16 summarize results from our multinomial logistic regression analyses, whereby we identified predictors of group membership for each trajectory model. Appendix D contains a glossary of the variables included in this analysis, along with corresponding definitions and sources.

In the non-imputed geographic equity dataset, we identified several predictors of membership in each group: in Group 2 (middle decreasing), income level, region, female education, political stability, corruption, out-of-pocket health expenditures, government expenditures on health, linguistic fractionalization, and distance (i.e., the proportion of the population more than 60 minutes by foot away from the nearest health facility); in Group 3 (middle-stable), income, region, political stability, government effectiveness, out-of-pocket health expenditures, government expenditures on health, external resources for health per capita, land area, and distance; in Group 4 (high-stable), income level, region, female education, government effectiveness, gender inequality, out-of-pocket health expenditures, government expenditures on health, external resources for health per capita, land area, linguistic fractionalization, and distance; and in Group 5 (middle-increasing), region, female education, political stability, gender inequality, land area, linguistic fractionalization, and distance. Notably, integration was not a significant predictor of membership in any of the five groups. Using the imputed dataset, however, we found that all of the variables included in the regression model were significant predictors of membership in Groups 1-4. With the exception of corruption, these variables were also significant predictors of Group 5 (middle-increasing) membership.

In the non-imputed socioeconomic equity dataset, we identified several significant predictors of Group 2 (medium decreasing) membership, including female education, gender inequality, government expenditures on health, external resources for health per capita, and land area. Female education, gender inequality, out-of-pocket health expenditures, government health expenditures, external resources for health per capita, land area, linguistic fractionalization, and distance were also significant predictors of membership in Group 3 (medium stable). Integration was not a significant predictor of membership in any group, nor did we identify any significant predictors of

Group 4 (high-inequity) membership using the non-imputed dataset. Using the imputed dataset, however, we found that with the exception of geographic region, every variable in the model – including integration – was a significant predictor of Group 2 (high-stable) membership.

Figure 10. Geographic Equity (non-imputed)

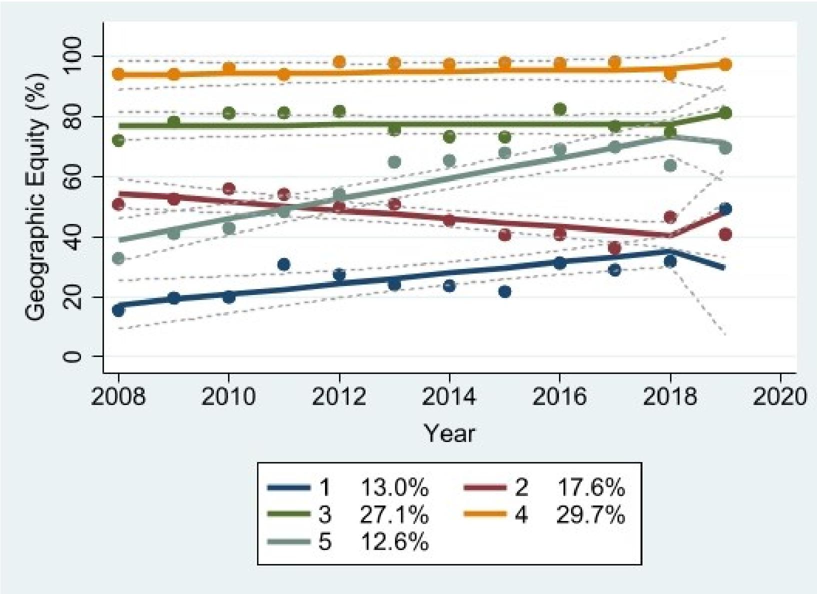


Figure 11. Socioeconomic Equity (non-imputed)

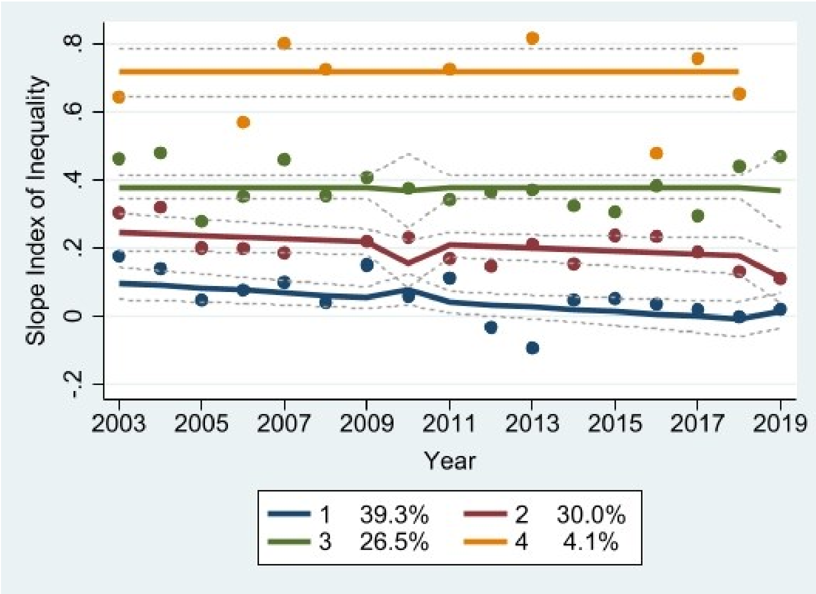


Figure 12. Geographic Equity (imputed)

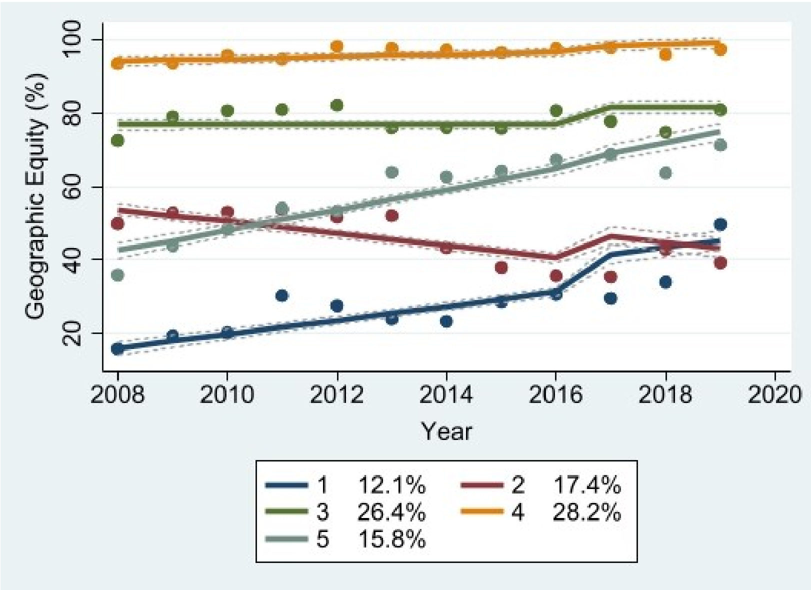
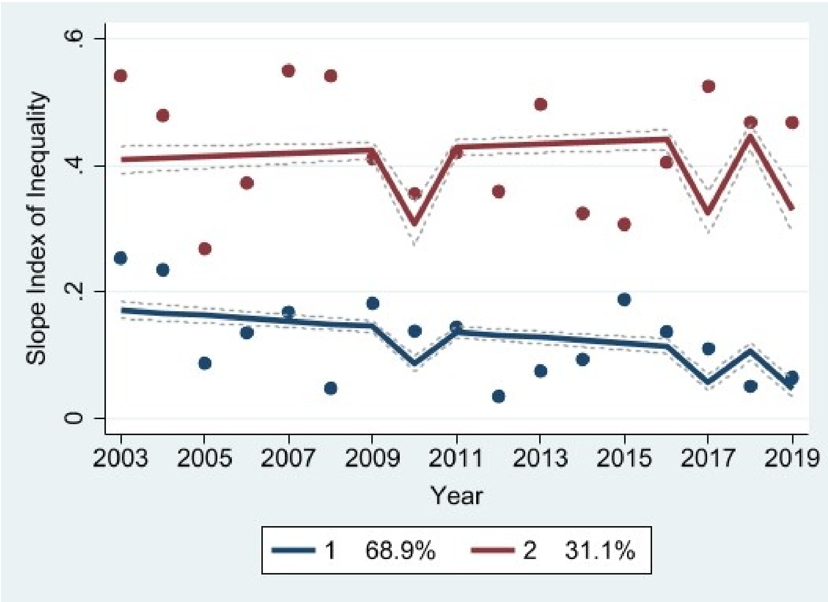


Figure 13. Socioeconomic Equity (imputed)



4.5 DISCUSSION

In this investigation, we applied GBTM – a method for summarizing complex longitudinal data – to examine the relationship between integrated vaccine delivery and vaccination equity in 78 LMICs that had ever received Gavi support. Using our non-imputed longitudinal dataset, we constructed models of geographic and socioeconomic equity consisting of five and four distinct equity trajectories (i.e., groups), respectively. Though integration was not a statistically significant predictor of group membership in either model, we identified a broad range of other important predictors (see Tables 9 and 10). Using the imputed dataset, we developed a second five-group geographic equity model, as well as a two-group socioeconomic equity model. With the exception of corruption, all of the variables included in the multinomial logistic regression – including integration – were significant predictors of group membership in the geographic equity model. Integration, along with all variables except geographic region, was also a significant predictor of membership in Group 2 (high-stable) of the imputed socioeconomic model.

The statistically significant association between integration and Groups 1-4 in the imputed geographic equity model carries similarly important implications for public health policy and practice. This finding suggests that integrated vaccine delivery is most strongly associated with equity improvements in settings with chronically low levels of equity (i.e., Group 1), followed by those reporting decreasing levels of equity over time (i.e., Group 2), and finally, in settings in which geographic equity has largely plateaued (i.e., Groups 3 and 4). However, it may have a weaker association with equitable vaccination coverage in settings like Group 5 countries, whose developmental trajectory commences at a middling level of equity and increases more rapidly than its counterparts in Groups 1-4. In the imputed model, integration was also a predictor of membership in all but the lowest-performing group (Group 1, low-increasing), further suggesting that integration is associated with high geographic equity achievement. Due to our small sample, we were unable to ascertain whether integration might have had small- or medium-sized associations with geographic equity in groups in which we detected no statistically significant associations between the two. Nevertheless, given that measles risk is often spatially clustered, this finding may be especially relevant for countries pursuing herd immunity against measles as part of a national or multi-district mitigation or elimination strategy.[367]

In the non-imputed model, integration showed a significant association with socioeconomic equity in Group 4 (high-inequity) countries: a 0.53-unit reduction in SII. In the imputed model, integration with associated with two additional statistically significant reductions in SII: a 0.054-unit drop in Group 1 (low-stable) and a 0.12-unit drop in Group 2 (high-stable). This finding suggests that integrated vaccine delivery may be most strongly associated with equity improvements in settings characterized by chronically high levels of vaccination inequity at baseline. In this vein, we found that the relative risk of a country being assigned to Group 2 (high-inequity) would decrease by a factor of 0.49 if the country in question achieved integration (see Table 15). In settings characterized by lower levels of socioeconomic inequity (i.e., Group 1 countries), integration may still have positive, albeit diminishing associations with equitable vaccination coverage. As with the geographic equity models, we were unable to detect small- or medium-sized associations due to our small sample size and the limited availability of socioeconomic equity data.

As previously discussed, the groups identified in this analysis are unobservable, latent constructs, and observed trajectories are not immutable; rather, grouping is simply an intuitive way of summarizing trends in vaccination equity across highly heterogenous settings. As such, neither the groups nor their estimated trajectories can predict future equity outcomes in any single country. The number of resultant trajectories and their associated paths will likely evolve as data availability improves for outcome measures, and as additional years' worth of data are incorporated, particularly with respect to socioeconomic equity. Though integration was not a significant predictor of membership in every group, our analyses do suggest an overall positive association between integrated vaccine delivery and both geographic and socioeconomic vaccination equity in LMICs that have ever received Gavi support. This finding resonates with calls to integrate standalone routine immunization programs into broader systems of care.[360,368–370]

Whether by reducing opportunities for missed vaccination or providing a "one-stop shop" for immunization and other essential health services, integrated vaccine delivery mechanisms may play important roles in shaping health equity.[368] Our finding that integration is most strongly associated with equity improvements in settings characterized by high baseline levels of geographic or socioeconomic inequity aligns with previous studies demonstrating that integrated health platforms can help resource-constrained settings achieve equitable population health outcomes.[21,371] Encouragingly, these findings also comport with health worker experiences delivering and patient experiences receiving integrated care. Reporting on focus groups held in four African countries, for example, Ryman et al. note that integration afforded patients greater convenience and access to needed services, reduced transportation times and costs, increased health service utilization and health worker efficiency, and reduced reporting requirements.[372] In this vein, our imputed dataset indicates that countries were likelier to belong to Group 2 (high-inequity) if they reported a significant degree of linguistic fractionalization (RR: 2.27 [CI: 1.45, 3.56]), high levels of gender inequality (RR: 3.34 [CI: 1.92, 5.82]), or long distances to the nearest health facility (RR: 1.02 [CI: 1.02, 1.03]). Thus, demand-side interventions targeting these factors could also play an important role in improving vaccination equity in LMICs.

This investigation does have several limitations, most of which relate to the quality and availability of our data. Across both datasets, the socioeconomic equity trajectories had wider confidence intervals and showed sharp fluctuations over the study period, reflecting the paucity of vaccination coverage data disaggregated by wealth quintile. Additionally, our measures of geographic equity and vaccination coverage were extracted from the WHO-UNICEF Joint Reporting Forms (JRF) on Immunization and WHO-UNICEF Estimates of Immunization Coverage (WUENIC). Previous analyses of JRFs suggest that while the accuracy and completeness of these forms improves over time and with greater familiarity, critical immunization data are still often missing.[373] In some cases, data provided in response to JRF questions draw from in-country assessments of unknown quality and rigor.[374] WUENIC, in turn, are created from JRF estimates, national administrative coverage estimates (which may be biased by inaccurate numerators or denominators), survey estimates (e.g., DHS and MICS), and other sources.[375] Furthermore, our measures of socioeconomic equity were calculated from DHS and MICS estimates of vaccination coverage by wealth quintile, which are available only for select years in a handful of countries. These coverage estimates may also carry a bias toward urbanized settings in some cases.[329] Policymakers and decision-makers in LMICs could thus support improved monitoring activities in LMICs by investing in stronger vaccination data collection capacities, systems, and workforces. Additionally, newer measures of equity – such as the Vaccine Economics Research for Sustainability and Equity (VERSE) composite vaccination equity assessment metric – may offer more a more sophisticated approach to accounting for the structural factors underpinning observed disparities in coverage between wealth quintiles or other axes of vulnerability.[376]

Additionally, despite the large number of observations per country and positive model diagnostics, our sample was relatively small, which limited the statistical power of this analysis and limited detection of small and medium associations between integration and equity, particularly in our non-imputed dataset. This challenge has also been documented in other GBTM analyses examining country-level phenomena.[355] Loughran and Nagin do report that robust GBTM analyses are possible with as few as 500 study subjects when using Poisson-based models, but whether this threshold applies to other models (e.g., censored normal, binary logit) and the absolute minimum sample size required to apply GBTM remain unknown.[377] Thus, further work is needed to determine how best to model developmental trajectories in inherently small samples.

Another critical limitation relates to the measurement of integrated vaccine delivery. Unlike other metrics of integration, the Working Group's measure is readily determined from publicly available data collected on a routine basis across all countries; therefore, its primary value lies in its convenience and accessibility. Conceptually, however, it is a flawed measure because it fails to account for the heterogeneity of integrated health service delivery or structural barriers that might impede a well-integrated system – for example, one with low but near-equal coverage across all services – from raising coverage to sufficiently high levels. As a result, this measure likely underestimates the number of countries to have achieved integrated vaccine delivery. Additionally, per Oliveira-Cruz et al., health system integration is best understood as a continuum ranging from highly vertical programs (e.g., the Global Polio Eradication Initiative) to robust horizontal systems (e.g., those that provide comprehensive primary care).[13] A quantitative measure of integration, therefore, should ideally exist on a continuous scale, unlike the Working Group's dichotomous indicator. Thus, more robust measures for monitoring integrated vaccine delivery in LMICs are urgently needed. A potential alternative – though, to our knowledge, one that is not reported publicly or readily computable – is the proportion of children under 5 who receive measles vaccinations via routine health programs versus vertical supplemental immunization activities, such as campaigns. Another option, albeit more complex, is a composite index that accounts for immunization program financing, workforce structure, modes of delivery, effective coverage, and barriers to vaccine access.

Despite these limitations, findings from this investigation could nevertheless inform efforts to evaluate integrated vaccine delivery in LMICs – an endeavor of particular significance as many LMIC countries grow wealthier and eventually transition away from Gavi support. Our findings could also support future studies of integration and vaccination equity. Follow-on qualitative case studies, for example, might compare and contrast processes of integration between countries in the low-increasing and high-stable geographic equity groups, identify barriers to integrated vaccine delivery among countries following a trajectory marked by high socioeconomic inequity, or consider potential demand-side interventions targeting mid-range wealth quintiles in the middle-increasing and -decreasing groups. Findings from these analyses, in turn, could support decision-making and resource allocation for vaccination equity-strengthening activities in LMICs.

Further work is also needed to explore potential causal mechanisms underpinning the associations identified in this investigation, particularly in the context of universal health coverage provision. In this vein, future analyses might examine whether countries with integrated vaccine delivery programs are more likely to offer health packages or insurance schemes that subsidize the cost of vaccination, thereby incentivizing uptake and resulting in increased coverage. Finally, GBTM itself could serve as a useful analytical tool for summarizing complex longitudinal data in public health studies where randomization is not possible.

4.6 CONCLUSION

Amid ongoing calls for universal health coverage, and in light of the persistent threat of vaccine-preventable diseases in LMICs, ensuring equitable vaccination remains an urgent public health imperative. The findings from this investigation – which applied GBTM to examine longitudinal trends in geographic and socioeconomic vaccination equity in 78 LMICs – suggest a positive association between integrated vaccine delivery and vaccination equity. Though continued scholarship is needed to further characterize the relationship between integration and health equity, this investigation constitutes a first step toward summarizing these complex phenomena at the country level.

Table 5. Observations Omitted from Multiple Imputation Regression Model

Country || Year	Number of Observations Omitted from Multiple Imputation Regression Model																	Total
	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	
Afghanistan	11	11	11	11	11	11	11	11	1	11	11	11	1	11	11	11	11	**167**
Albania	11	11	11	11	11	11	1	11	11	11	11	11	11	11	11	1	11	**167**
Angola	11	11	11	11	11	11	11	11	11	11	11	11	11	1	11	11	11	**177**
Armenia	11	11	1	11	11	11	11	1	11	11	11	11	11	11	11	11	11	**167**
Azerbaijan	11	11	11	1	11	11	11	11	11	11	11	11	11	11	11	11	11	**177**
Bangladesh	11	1	11	1	1	11	11	11	1	11	11	1	11	11	11	1	11	**127**
Benin	11	11	11	1	11	11	11	11	11	1	11	1	11	11	11	1	11	**147**
Bhutan	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Bolivia	1	11	11	11	11	1	11	11	11	11	11	11	11	11	11	11	11	**167**
Bosnia & Herzegovina	11	11	11	1	11	11	11	11	11	1	11	11	11	11	11	11	11	**167**
Burkina Faso	1	11	11	1	11	11	11	1	11	11	11	11	11	11	11	11	11	**157**
Burundi	11	11	1	11	11	11	11	1	11	11	11	11	11	11	1	11	11	**157**
Cambodia	11	11	1	11	11	11	11	1	11	11	11	1	11	11	11	11	11	**157**
Cameroon	11	1	11	11	11	11	11	11	1	11	11	1	11	11	11	1	11	**147**
Central African Reublic	11	11	11	1	11	11	11	1	11	11	11	11	11	11	11	11	1	**157**
Chad	11	1	11	11	11	11	11	1	11	11	11	11	1	11	11	11	1	**147**
China	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Comoros	11	11	11	11	11	11	11	11	11	1	11	11	11	11	11	11	11	**177**
Cuba	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Democratic People's Republic of North Korea	11	11	11	11	11	11	11	11	11	11	11	11	11	11	1	11	11	**177**
Democratic Republic of the Congo	11	11	11	11	1	11	11	1	11	11	11	1	11	11	11	1	11	**147**
Djibouti	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Eritrea	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Ethiopia	11	11	1	11	11	11	11	11	1	11	11	11	11	1	11	11	1	**147**
Gambia	11	11	11	1	11	11	11	1	11	11	1	11	11	11	11	1	11	**147**
Georgia	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Ghana	1	11	11	1	11	1	11	11	1	11	11	1	11	11	11	1	11	**127**
Guinea	11	11	1	11	11	11	11	11	11	1	11	11	11	1	11	1	11	**147**
Guinea-Bissau	11	11	11	1	11	11	11	1	11	11	11	1	11	11	11	11	1	**147**
Guyana	11	11	11	11	1	11	1	11	11	11	11	1	11	11	11	11	11	**157**
Haiti	11	11	11	1	11	11	11	11	11	1	11	11	11	11	1	11	11	**157**
Honduras	11	11	11	1	11	11	11	11	11	1	11	11	11	11	11	11	11	**167**
India	11	11	11	1	11	11	11	11	11	11	11	11	11	1	11	11	11	**167**
Indonesia	1	11	11	11	1	11	11	11	11	1	11	11	11	11	1	11	11	**147**
Ivory Coast	11	11	11	1	11	11	11	11	11	1	11	11	11	1	11	11	11	**157**
Kenya	1	11	11	11	11	11	1	11	11	11	11	1	11	11	11	11	11	**157**
Kiribati	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	1	**177**
Kyrgyzstan	11	11	11	11	11	11	11	11	11	1	11	1	11	11	11	1	11	**157**
Lao People's Democratic Republic	11	11	11	1	11	11	11	11	1	11	11	11	11	11	1	11	11	**157**

Table 5, Continued. Observations Omitted from Multiple Imputation Regression Model

	Number of Observations Omitted from Multiple Imputation Regression Model																	
Country || Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	**Total**
Lesotho	11	1	11	11	11	11	1	11	11	11	11	1	11	11	11	1	11	**147**
Liberia	11	11	11	11	1	11	11	11	11	11	1	11	11	1	11	11	11	**157**
Madagascar	11	1	11	11	11	11	1	11	11	1	11	11	11	11	11	1	11	**147**
Malawi	11	1	11	1	11	11	11	1	11	11	11	1	11	1	11	11	11	**137**
Mali	11	11	11	1	11	11	11	1	11	11	1	11	1	11	11	1	11	**137**
Mauritania	11	11	11	11	1	11	11	11	1	11	11	11	1	11	11	11	11	**157**
Moldova	11	11	1	11	11	11	11	11	11	1	11	11	11	11	11	11	11	**167**
Mongolia	11	11	1	11	11	11	11	1	11	11	11	1	11	11	11	1	11	**147**
Mozambique	1	11	11	11	11	1	11	11	1	11	11	11	1	11	11	11	11	**147**
Myanmar	11	11	11	11	11	11	11	1	11	11	11	11	11	1	11	11	11	**167**
Nepal	11	11	11	1	11	11	11	1	1	11	11	1	11	1	11	11	1	**127**
Nicaragua	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Niger	11	11	11	1	11	11	11	11	11	1	11	11	11	11	11	11	11	**167**
Nigeria	1	11	11	11	1	1	11	11	1	11	1	11	11	11	1	1	11	**117**
Pakistan	11	11	11	11	1	11	11	11	11	11	1	11	11	11	11	1	11	**157**
Papua New Guinea	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	1	11	**177**
Republic of the Congo (Brazzaville)	11	11	1	11	11	11	11	11	11	1	11	11	1	11	11	11	11	**157**
Rwanda	11	11	1	11	11	1	11	1	11	11	11	11	1	11	11	11	11	**147**
Sao Tome & Principe	11	11	11	1	11	11	1	11	11	11	11	1	11	11	11	11	1	**147**
Senegal	11	11	1	11	11	11	11	11	1	11	1	1	1	1	1	1	1	**97**
Sierra Leone	11	11	1	11	11	1	11	1	11	11	1	11	11	11	1	11	1	**127**
Solomon Islands	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Somalia	11	11	11	1	11	11	11	11	11	11	11	11	11	11	11	11	11	**177**
South Sudan	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Sri Lanka	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	**187**
Sudan	11	11	11	11	11	11	11	1	11	11	11	1	11	11	11	11	11	**167**
Syria	11	11	11	1	11	11	11	11	11	11	11	11	11	11	11	11	11	**177**
Tajikistan	11	11	1	11	11	11	11	11	11	1	11	11	11	11	1	11	11	**157**
Tanzania	11	11	1	11	11	11	11	1	11	11	11	11	11	1	11	11	11	**157**
Timor-Leste	11	11	11	11	11	11	1	11	11	11	11	11	11	1	11	11	11	**167**
Togo	11	11	11	1	11	11	11	1	11	11	11	1	11	11	1	11	11	**147**
Turkmenistan	11	11	11	1	11	11	11	11	11	11	11	11	11	1	11	11	11	**167**
Uganda	11	11	11	1	11	11	11	11	1	11	11	11	11	1	11	11	11	**157**
Ukraine	11	11	11	11	11	11	11	11	11	1	11	11	11	11	11	11	11	**177**
Uzbekistan	11	11	11	1	11	11	11	11	11	11	11	11	11	11	11	11	11	**177**
Vietnam	11	11	11	11	11	11	11	11	1	11	11	1	11	11	11	11	11	**167**
Yemen	11	11	11	1	11	11	11	11	11	11	1	11	11	11	11	11	11	**167**
Zambia	11	11	11	11	1	11	11	11	11	11	11	1	11	11	11	1	11	**157**
Zimbabwe	11	11	11	1	11	11	1	11	1	11	11	1	1	11	11	11	1	**127**
TOTAL	**788**	**798**	**728**	**588**	**768**	**798**	**778**	**668**	**718**	**708**	**778**	**648**	**768**	**718**	**758**	**678**	**758**	**12,446**

	Table 6. Group-Based Trajectory Model Diagnostics			
	Geographic Equity (non-imputed model)	**Geographic Equity (imputed model)**	**Socioeconomic Equity (non-imputed model)**	**Socioeconomic Equity (imputed model)**
Model Diagnostics				
Bayesian information criterion	-3786.16	-44042.75	109.11	1089.08
Entropy	0.951	0.896	0.701	0.735
Average posterior probability of group assignment	Group 1: 0.995 Group 2: 0.967 Group 3: 0.962 Group 4: 0.974 Group 5: 0.959	Group 1: 0.998 Group 2: 0.941 Group 3: 0.928 Group 4: 0.978 Group 5: 0.932	Group 1: 0.783 Group 2: 0.838 Group 3: 0.919 Group 4: 0.887	Group 1: 0.908 Group 2: 0.935
Odds of correct group classification	Group 1: 1419.48 Group 2: 135.58 Group 3: 70.24 Group 4: 91.29 Group 5: 159.73	Group 1: 2992.39 Group 2: 72.95 Group 3: 34.12 Group 4: 117.37 Group 5: 73.70	Group 1: 3.99 Group 2: 14.98 Group 3: 37.65 Group 4: 195.76	Group 1: 3.45 Group 2: 41.16

This table presents several diagnostics for each of our group-based trajectory models. Per Nagin, Bayesian information criterion values and entropy values should be as large as possible, average posterior probabilities should be at least 0.7, and the odds of correct classification should ideally be 5 or greater.

	Total	Non-Imputed Dataset		Imputed Dataset	
	Countries *N* (%)	Mean geographic equity (SD)	Mean socioeconomic equity (SD)	Mean geographic equity (SD)	Mean socioeconomic equity (SD)
Region					
East Asia and the Pacific	12 (15.4)	67.71 (31.72)	0.193 (0.160)	67.4 (31.88)	0.193 (0.157)
Europe and Central Asia	11 (14.1)	92.8 (19.0)	-0.0053 (0.102)	88.1 (25.53)	-0.0053 (0.0998)
Latin America and the Caribbean	6 (7.7)	75.56 (29.16)	0.0923 (0.150)	75.78 (29.09)	0.0923 (0.143)
Middle East and North Africa	2 (2.6)	47.36 (24.29)	0.273 (0.164)	48.19 (23.8)	0.273 (0.136)
South Asia	7 (9)	75.68 (20.49)	0.214 (0.187)	74.64 (21.4)	0.214 (0.182)
Sub-Saharan Africa	40 (51.3)	62.36 (26.64)	0.246 (0.189)	62.11 (26.87)	0.246 (0.188)
Income Level					
Low-income	28 (35.9)	63.74 (26.51)	0.222 (0.167)	63.43 (26.81)	0.222 (0.166)
Lower-middle-income	40 (51.3)	65.99 (29.01)	0.223 (0.202)	65.32 (29.46)	0.223 (0.202)
Upper-middle-income	10 (12.8)	95.32 (12.46)	0.011 (.134)	94.5 (14.78)	0.011 (0.13)

Table 7. Summary of Country Characteristics

This table reflects regional and income level classifications as specified by the World Bank in 2022. Geographic equity refers to the proportion of districts within a country that have achieved 80% MCV1 coverage or greater. Socioeconomic equity refers to the slope index of inequality (SII) based on MCV1 coverage by wealth quintile. Larger SII values indicate that higher MCV1 coverage is more prevalent among wealthier quintiles.

Table 8. Integrated Vaccine Delivery by Country, 2003-2019			
Country	Integration Score		Total Observations
	0	1	
Afghanistan	17	0	17
Albania	17	0	17
Angola	17	0	17
Armenia	17	0	17
Azerbaijan	17	0	17
Bangladesh	17	0	17
Benin	17	0	17
Bhutan	15	2	17
Bolivia	16	1	17
Bosnia & Herzegovina	17	0	17
Burkina Faso	15	2	17
Burundi	16	1	17
Cambodia	16	1	17
Cameroon	14	3	17
Central African Republic	17	0	17
Chad	17	0	17
China	17	0	17
Comoros	16	1	17
Cuba	17	0	17
Democratic People's Republic of Korea	15	2	17
Democratic Republic of the Congo	17	0	17
Djibouti	16	1	17
Eritrea	16	1	17
Ethiopia	17	0	17
Gambia	14	3	17
Georgia	17	0	17
Ghana	11	6	17
Guinea	17	0	17
Guinea-Bissau	17	0	17
Guyana	14	3	17
Haiti	17	0	17
Honduras	15	2	17
India	16	1	17
Indonesia	17	0	17
Ivory Coast	17	0	17
Kenya	17	0	17
Kiribati	15	2	17
Kyrgyzstan	17	0	17
Lao People's Democratic Republic	17	0	17
Lesotho	15	2	17
Liberia	17	0	17
Madagascar	17	0	17
Malawi	16	1	17
Mali	17	0	17
Mauritania	17	0	17

Table 8, Continued. Integrated Vaccine Delivery by Country, 2003-2019			
Country	Integration Score		Total Observations
	0	1	
Moldova	17	0	17
Mongolia	17	0	17
Mozambique	15	2	17
Myanmar	16	1	17
Nepal	15	2	17
Nicaragua	17	0	17
Niger	17	0	17
Nigeria	17	0	17
Pakistan	16	1	17
Papua New Guinea	17	0	17
Republic of the Congo (Brazzaville)	17	0	17
Rwanda	15	2	17
Sao Tome & Principe	14	3	17
Senegal	13	4	17
Sierra Leone	16	1	17
Solomon Islands	17	0	17
Somalia	17	0	17
South Sudan	17	0	17
Sri Lanka	14	3	17
Sudan	16	1	17
Syria	17	0	17
Tajikistan	17	0	17
Tanzania	15	2	17
Timor-Leste	17	0	17
Togo	15	2	17
Turkmenistan	17	0	17
Uganda	17	0	17
Ukraine	17	0	17
Uzbekistan	17	0	17
Vietnam	14	3	17
Yemen	17	0	17
Zambia	17	0	17
Zimbabwe	16	1	17
Total	**1,263**	**63**	**1326**

* This table displays the number of years in which a country earned a given integration score (0 or 1) over the course of the 17-year study period (2003-2019).

0: coverage levels of MCV1, PAB, ANC1, and DTP3 are all below 70%

1: coverage of at least one of the four services is at or above 70%

		Table 9. Maximum Likelihood Estimates: Geographic Equity							
		Non-Imputed Dataset				Imputed Dataset			
Model Parameter Estimates									
Group	**Parameter**	**Estimate**	**Error**	**t**	**Probability > |t|**	**Estimate**	**Error**	**t**	**Probability > |t|**
1 ("Low-increasing")	Intercept	-3726.42	884.47	-4.21	0.00	-3828.30	288.24	-13.28	0.00
	Linear	1.86	0.44	4.24	0.00	1.91	0.14	13.37	0.00
	Integration	-7.71	8.93	-0.86	0.39	8.32	1.28	6.49	0.00
2 ("Middle-increasing")	Intercept	2864.77	732.59	3.91	0.0001	3404.92	248.98	13.68	0.00
	Linear	1.40	0.36	-3.85	0.0001	-1.67	0.12	-13.49	0.00
	Integration	9.01	7.24	1.24	0.21	7.90	1.22	6.49	0.00
3 ("Middle-stable")	Intercept	8.82	584.72	0.015	0.99	40.05	195.75	0.21	0.84
	Linear	0.034	0.29	0.12	0.91	0.018	0.097	0.19	0.85
	Integration	3.87	3.73	1.04	0.30	4.60	0.76	6.09	0.00
4 ("High-stable")	Intercept	-368.32	546.35	-0.67	0.50	-498.04	180.17	-2.76	0.006
	Linear	0.23	0.27	0.85	0.40	0.29	0.089	3.30	0.001
	Integration	1.75	3.46	0.51	0.61	1.58	0.67	2.37	0.018
5 ("High-stable")	Intercept	-6808.17	1061.15	-6.42	0.00	-5519.41	385.43	-14.32	0.00
	Linear	3.41	0.53	6.47	0.00	2.77	0.19	14.47	0.00
	Integration	-5.38	6.54	-0.82	0.41	1.72	1.25	1.37	0.17
Group Membership									
1 ("Low-increasing")		13.04%	3.92	3.33	0.009	12.07%	1.14	10.63	0.00
2 ("Middle-increasing")		17.62%	4.50	3.92	0.0001	17.45%	1.43	12.21	0.00
3 ("Middle-stable")		27.05%	5.41	5.00	0.00	26.44%	1.66	15.96	0.00
4 ("High-stable")		29.68%	5.53	5.37	0.00	28.23%	1.68	16.80	0.00
5 ("High-stable")		12.61%	4.08	3.10	0.002	15.80%	1.48	10.71	0.00

Table 10. Maximum Likelihood Estimates: Socioeconomic Equity											
Non-Imputed Dataset						Imputed Dataset					
Model Parameter Estimates											
Group	**Parameter**	**Estimate**	**Error**	**t**	**Probability > |t|**	**Group**	**Parameter**	**Estimate**	**Error**	**t**	**Probability > |t|**
1 ("Low-inequity")	Intercept	14.12	5.24	2.70	0.008	**1 ("Low-stable")**	Intercept	8.93	1.43	6.25	0.00
	Linear	-0.01	0.003	-2.69	0.008		Linear	-0.0044	0.00071	-6.15	0.00
	Integration	0.03	0.03	1.12	0.26		Integration	-0.0054	0.00075	-7.20	0.00
2 ("Medium-decreasing")	Intercept	9.46	5.63	1.68	0.09	**2 ("High-stable")**	Intercept	-4.48	2.20	-2.04	0.04
	Linear	-0.005	0.003	-1.64	0.10		Linear	0.0024	0.0011	2.23	0.026
	Integration	0.06	0.04	-1.64	0.10		Integration	-0.12	0.018	-6.63	0.000
3 ("Medium-stable")	Intercept	0.38	0.02	23.21	0.00						
	Integration	-0.012	0.06	-0.20	0.84						
4 ("High-inequity")	Intercept	0.72	0.03	20.52	0						
	Integration	-0.53	0.13	-4.06	0.0001						
Group Membership											
1 ("Low-inequity")		39.33%	7.52	5.23	0.00	**1 ("Low-stable")**		68.85%	1.98	34.70	0.00
2 ("Medium-decreasing")		30.01%	7.56	3.97	0.0001	**2 ("High-stable")**		31.15%	1.98	15.70	0.00
3 ("Medium-stable")		26.53%	6.34	4.19	0.00						
4 ("High-inequity")		4.12%	2.75	1.50	0.14						

		Table 11. Parametric Bootstrap Sampling Confidence Interval Estimates: Geographic Equity									
		Non-Imputed Dataset					Imputed Dataset				
Group	Parameter	Observed Coefficient	Bootstrap Standard Error	*z*	Probability > |z|	95% Confidence Interval (Bias Corrected)	Observed Coefficient	Bootstrap Standard Error	*z*	Probability > |z|	95% Confidence Interval (Bias Corrected)
1 ("Low-increasing")	Intercept	-3726.40	1938.31	-1.92	0.06	(-9566.50, -874.15)	-3828.3	731.08	-5.24	0.00	(-4910.96, -2069.20)
	Linear	1.86	0.96	1.93	0.053	(0.45, 4.77)	1.91	0.36	5.27	0.00	(1.04, 2.45)
	Integration	-6.34	244.96	-0.03	0.98	(-12.20, 17.89)	8.32	1.62	5.13	0.00	(4.82, 11.31)
2 ("Middle-decreasing")	Intercept	2864.78	1188.38	2.41	0.016	(830.46, 5644.19)	3404.92	381.61	8.92	0.00	(2790.18, 4177.75)
	Linear	-1.40	0.59	-2.37	0.018	(-2.78, -0.39)	-1.67	0.19	-8.79	0.00	(-2.05, -1.36)
	Integration	8.88	26.74	0.33	0.74	(-0.94, 29.86)	7.89	1.24	6.38	0.00	(5.46, 10.23)
3 ("Middle-stable")	Intercept	8.82	1878.30	0.00	1.00	(-1935.68, 11040.6)	40.05	457.94	0.09	0.93	(-777.67, 968.02)
	Linear	0.033	0.93	0.04	0.97	(-5.44, 0.997)	0.02	0.23	0.08	0.94	(-0.44, 0.42)
	Integration	3.87	206.70	0.02	0.99	(-2.42, 7.85)	4.60	0.94	4.87	0.00	(2.50, 6.30)
4 ("High-stable")	Intercept	-368.32	489.78	-0.75	0.45	(-1181.89, 874.43)	-498.04	143.88	-3.46	0.001	(-787.43, -212.46)
	Linear	0.23	0.24	0.95	0.34	(-0.42, 0.63)	0.29	0.07	4.12	0.00	(0.15, 0.44)
	Integration	1.75	1.29	1.35	0.18	(-1.20, 4.04)	1.58	0.45	3.51	0.00	(0.83, 2.60)
5 ("Middle-increasing")	Intercept	-6808.17	2782.72	-2.45	0.014	(-11790.93, -1102.48)	-5519.41	1548.90	-3.56	0.00	(-9723.36, -3875.15)
	Linear	3.41	1.38	2.47	0.013	(0.58, 5.88)	2.77	0.77	3.61	0.00	(1.95, 4.85)
	Integration	-5.41	1062.51	-0.01	0.996	(-644.69, 287.75)	1.72	2.90	0.59	0.55	(-2.45, 9.01)

	Table 12. Parametric Bootstrap Sampling Confidence Interval Estimates: Socioeconomic Equity											
	Non-Imputed Dataset						Imputed Dataset					
Group	**Parameter**	**Observed Coefficient**	**Bootstrap Standard Error**	***z***	**Probability > |*z*|**	**95% Confidence Interval (Bias Corrected)**	**Parameter**	**Observed Coefficient**	**Bootstrap Standard Error**	***z***	**Probability > |*z*|**	**95% Confidence Interval (Bias Corrected)**
1	Intercept	14.12	6.15	2.30	0.022	(-1.22, 23.94)	Intercept	8.93	1.59	5.61	0.00	(5.42, 11.71)
	Linear	-0.007	0.003	-2.29	0.022	(-0.012, 0.00054)	Linear	-0.004	0.0008	-5.50	0.00	(-0.006, -0.003)
	Integration	0.031	0.04	0.79	0.43	(-0.05, .10)	Integration	-0.05	0.01	-4.56	0.00	(-0.08, -0.04)
2	Intercept	9.46	8.85	1.07	0.29	(-12.91, 22.51)	Intercept	-4.48	1.58	-2.83	0.005	(-7.48, -1.21)
	Linear	-0.005	0.0044	-1.04	0.30	(-0.011, 0.007)	Linear	0.0024	0.0008	3.11	0.002	(0.0008, 0.004)
	Integration	-0.061	0.06	-0.98	0.33	(-0.26, 0.018)	Integration	-0.12	0.03	-4.14	0.00	(-0.17, -0.08)
3	Intercept	0.38	0.03	12.7	0.00	(0.33, 0.47)						
	Integration	-0.011	0.09	-0.13	0.90	(-0.35, 0.09)						
4	Intercept	0.72	0.14	5.01	0.00	(0.41, 0.74)						
	Integration	-0.53	0.21	-2.50	0.012	(-0.87, -0.25)						

	Table 13. Country Group Membership	
	Non-Imputed Dataset	**Imputed Dataset**
Geographic Equity		
Group 1	Central African Republic, Eritrea, Haiti, Lesotho, Mauritania, Papua New Guinea, Solomon Islands, Somalia, Timor-Leste, Ukraine	Central African Republic, Eritrea, Haiti, Lesotho, Mauritania, Papua New Guinea, Solomon Islands, Somalia, Timor-Leste, Ukraine
Group 2	Afghanistan, Angola, Bolivia, Cameroon, Chad, Comoros, Djibouti, Guinea-Bissau, Kenya, Liberia, Republic of the Congo (Brazzaville), South Sudan, Syria, Yemen	Afghanistan, Angola, Bolivia, Bosnia & Herzegovina, Cameroon, Chad, Comoros, Djibouti, Guinea-Bissau, Kenya, Liberia, Republic of the Congo (Brazzaville), South Sudan, Ukraine, Yemen
Group 3	Benin, Bosnia & Herzegovina, Burundi, Cambodia, Democratic Republic of the Congo, Ghana, Guinea, Honduras, India, Indonesia, Kiribati, Madagascar, Malawi, Mali, Mongolia, Mozambique, Myanmar, Niger, Sierra Leone, Togo Zambia	Benin, Bhutan, Bosnia & Herzegovina, Burundi, Cambodia, Democratic Republic of the Congo, Ghana, Guinea, Honduras, India, Indonesia, Kiribati, Kyrgyzstan, Madagascar, Malawi, Mali, Mongolia, Mozambique, Myanmar, Niger, Rwanda, Sierra Leone, Syria, Tanzania, Togo, Zambia
Group 4	Albania, Armenia, Azerbaijan, Bangladesh, Bhutan, Burkina Faso, China, Cuba Democratic People's Republic of Korea, Gambia, Georgia, Guyana, Kyrgyzstan, Moldova, Nicaragua, Rwanda, Sao Tome & Principe, Sri Lanka, Tajikistan, Tanzania, Turkmenistan, Uzbekistan, Vietnam	Albania, Armenia, Azerbaijan, Bangladesh, Bhutan, Burkina Faso, China, Cuba, Democratic People's Republic of Korea, Gambia, Georgia, Guyana, Kyrgyzstan, Moldova, Nicaragua, Rwanda, Sao Tome and Principe, Sri Lanka, Tajikistan, Tanzania, Turkmenistan, Uzbekistan, Vietnam
Group 5	Ethiopia, Ivory Coast, Lao People's Democratic Republic, Nepal, Nigeria, Pakistan, Senegal, Sudan, Uganda, Zimbabwe	Ethiopia, India, Ivory Coast, Kiribati, Lao People's Democratic Republic, Nepal, Nigeria, Pakistan, Senegal, Sudan, Syria, Uganda, Zimbabwe

	Table 13, Continued. Country Group Membership	
	Non-Imputed Dataset	**Imputed Dataset**
Socioeconomic Equity		
Group 1	Afghanistan, Albania, Armenia, Bhutan, Bolivia, Bosnia & Herzegovina, Burundi, China, Cuba, Democratic People's Republic of Korea, Djibouti, Eritrea, Gambia, Georgia, Ghana, Guyana, Honduras, Kiribati, Kyrgyzstan, Lesotho, Malawi, Moldova, Mongolia, Nepal, Nicaragua, Rwanda, Sao Tome & Principe, Sierra Leone, Solomon Islands, Sri Lanka, Syria, Tajikistan, Turkmenistan, Uganda, Ukraine, Uzbekistan, Vietnam	Afghanistan, Albania, Armenia, Azerbaijan, Bangladesh, Bhutan, Bolivia, Bosnia & Herzegovina, Burkina Faso, Burundi, Cambodia, Chad, China, Comoros, Cuba, Democratic People's Republic of Korea, Djibouti, Eritrea, Gambia, Georgia, Ghana, Guinea-Bissau, Guyana, Haiti, Honduras, Indonesia, Kenya, Kiribati, Kyrgyzstan, Lesotho, Malawi, Mali, Mauritania, Moldova, Mongolia, Myanmar, Nepal, Nicaragua, Niger, Rwanda, Sao Tome & Principe, Senegal, Sierra Leone, Solomon Islands, Somalia, Sri Lanka, Syria, Tajikistan, Tanzania, Timor-Leste, Togo, Turkmenistan, Uganda, Ukraine, Uzbekistan, Vietnam, Zambia
Group 2	Azerbaijan, Bangladesh, Burkina Faso, Cambodia, Chad, Comoros, Guinea-Bissau, Haiti, Indonesia, Kenya, Mali, Mauritania, Myanmar, Niger, Senegal, Somalia, Tanzania, Togo, Zambia, Zimbabwe	Angola, Benin, Cambodia, Cameroon, Central African Republic, Democratic Republic of the Congo, Ethiopia, Guinea, India, Ivory Coast, Lao People's Democratic Republic, Liberia, Madagascar, Mozambique, Nigeria, Pakistan, Papua New Guinea, Republic of the Congo (Brazzaville), South Sudan, Sudan, Yemen
Group 3	Benin, Cameroon, Central African Republic Democratic Republic of the Congo, Ethiopia, Guinea, Ivory Coast, Lao People's Democratic Republic Liberia, Madagascar, Mozambique, Pakistan, Papua New Guinea, Republic of the Congo (Brazzaville), South Sudan, Sudan, Timor-Leste, Yemen	
Group 4	Angola, India, Nigeria	

		Table 14. Predictors of Group Membership: Geographic Equity									
		Non-Imputed Dataset					Imputed Dataset				
Group	Predictor of Group Membership	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval
1 (base outcome)											
2	Income	1.23E-06	8.00E-06	-2.1	0.036	(3.65E-12, 0.4159266)	3.74E-06	6.04E-06	-7.73	0	(1.58E-07, 0.000089)
	Region	4.44E-06	0.0000237	-2.3	0.021	(1.24E-10, 0.1587821)	0.0000608	0.0000681	-8.66	0	(6.75E-06, 0.00055)
	Female education	1.525187	0.2805218	2.3	0.022	(1.06, 2.19)	1.407719	0.064385	7.48	0	(1.29, 1.54)
	Political stability	3.07E+07	2.25E+08	2.35	0.019	(18.00, 5.25E+13)	578528.8	818782.5	9.37	0	(36110.48, 9268656)
	Government effectiveness	1308098	1.09E+07	1.69	0.091	(0.11, 1.61E+13)	608730	1170825	6.92	0	(14035.65, 2.64E+07)
	Corruption	6.60E-07	3.84E-06	-2.44	0.015	(7.29E-12, 0.06)	5.59E-06	7.30E-06	-9.26	0	(4.32E-07, 0.000072)
	Gender inequality	5.50E+10	8.58E+11	1.59	0.113	(0.003, 1.04E+24)	1.15E+08	3.72E+08	5.73	0	(202035.3, 6.53E+10)
	Out-of-pocket health expenditures	2.00891	0.5730435	2.45	0.014	(1.15, 3.51)	1.756889	0.102976	9.61	0	(1.57, 1.97)
	Government expenditures on health	1.021184	0.0105531	2.03	0.043	(1.00, 1.04)	1.018376	0.0032607	5.69	0	(1.01, 1.02)
	External resources for health per capita	1.140063	0.0779493	1.92	0.055	(0.997, 1.30)	1.089446	0.0184386	5.06	0	(1.05, 1.13)
	Land area	1.000014	7.64E-06	1.81	0.07	(1.00, 1.00)	1.000011	1.62E-06	6.48	0	(1.00, 1.00)
	Linguistic fractionalization	1.68E+19	3.01E+20	2.47	0.014	(9140.60, 3.08E+34)	2.45E+14	9.17E+14	8.85	0	(1.59E+11, 3.77E+17)
	Distance	0.3060222	0.1342392	-2.7	0.007	(0.13, 0.72)	0.3788097	0.0354667	-10.37	0	(0.32, 0.46)
	Integration	1.971843	8.303408	0.16	0.872	(0.0005, 7573.06)	2.739571	1.319636	2.09	0.036	(1.07, 7.04)

		Table 14, Continued. Predictors of Group Membership: Geographic Equity									
		Non-Imputed Dataset					Imputed Dataset				
Group	Predictor of Group Membership	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval
3	Income	1.32E-08	8.78E-08	-2.73	0.006	(2.89E-14, 0.0060)	1.30E-07	2.12E-07	-9.72	0	(5.32E-09, 3.18E-06)
	Region	1.46E-07	7.84E-07	-2.93	0.003	(3.83E-12, 0.006)	2.73E-06	3.08E-06	-11.35	0	(2.98E-07, 0.000025)
	Female education	1.41196	0.2608275	1.87	0.062	(0.98, 2.03)	1.322125	0.0605102	6.1	0	(1.21, 1.45)
	Political stability	5.05E+07	3.73E+08	2.4	0.016	(26.09,	479464.5	681700.5	9.2	0	(29547.59, 7780204)
	Government effectiveness	2.59E+09	2.21E+10	2.54	0.011	(137.61, 4.86E+16)	2.05E+08	3.98E+08	9.87	0	(4576649, 9.19E+09)
	Corruption	0.0000239	0.0001387	-1.84	0.066	(2.78E-10, 2.06)	0.0001559	0.0002022	-6.76	0	(0.000012, 0.002)
	Gender inequality	1.58E+12	2.48E+13	1.79	0.074	(0.069, 3.62E+25)	1.47E+09	4.79E+09	6.49	0	(2501470, 8.66E+11)
	Out-of-pocket health expenditures	2.144334	0.6211507	2.63	0.008	(1.22, 3.78)	1.840724	0.1088122	10.32	0	(1.64, 2.07)
	Government expenditures on health	0.9566394	0.0154208	-2.75	0.006	(0.93, 0.99)	0.9690138	0.0042717	-7.14	0	(0.96, 0.98)
	External resources for health per capita	1.223744	0.0817922	3.02	0.003	(1.07, 1.40)	1.146691	0.0184705	8.5	0	(1.11, 1.18)
	Land area	1.000021	7.89E-06	2.67	0.008	(1.00, 1.00)	1.000016	1.67E-06	9.5	0	(1.00, 1.00)
	Linguistic fractionalization	7.57E+13	1.32E+15	1.83	0.067	(0.10, 5.57E+28)	8.38E+10	3.09E+11	6.81	0	(6.00E+07, 1.17E+14)
	Distance	0.251116	0.1111677	-3.12	0.002	(0.11, 0.60)	0.323638	0.0305345	-11.96	0	(0.27, 0.39)
	Integration	6.282047	25.61232	0.45	0.652	(0.0021, 18556.93)	6.276409	2.964913	3.89	0	(2.49, 15.84)

		Table 14, Continued. Predictors of Group Membership: Geographic Equity									
		Non-Imputed Dataset					Imputed Dataset				
Group	Predictor of Group Membership	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval
4	Income	1.73E-07	1.14E-06	-2.36	0.018	(4.21E-13, 0.071)	6.08E-07	9.87E-07	-8.81	0	(2.52E-08, 0.0000147)
	Region	2.40E-07	1.29E-06	-2.84	0.005	(6.37E-12, 0.0090)	7.78E-06	8.77E-06	-10.43	0	(8.53E-07, 0.0000709)
	Female education	1.490188	0.2786829	2.13	0.033	(1.03, 2.15)	1.328794	0.0610553	6.19	0	(1.21, 1.45)
	Political stability	1073.834	7780.397	0.96	0.335	(0.00073, 1.58E+09)	564.8665	807.5557	4.43	0	(34.28, 9308.02)
	Government effectiveness	5.32E+12	4.71E+13	3.31	0.001	(153471.1, 1.85E+20)	3.67E+10	7.27E+10	12.28	0	(7.56E+08, 1.78E+12)
	Corruption	0.013079	0.0742058	-0.76	0.445	(1.94E-07, 883.11)	0.0259146	0.0332418	-2.85	0.004	(0.0021, 0.32)
	Gender inequality	4.04E+13	6.45E+14	1.96	0.05	(1.01, 1.62E+27)	5.66E+09	1.90E+10	6.7	0	(7951203, 4.03E+12)
	Out-of-pocket health expenditures	2.444354	0.7286869	3	0.003	(1.36, 4.38)	2.030428	0.1229884	11.69	0	(1.80, 2.29)
	Government expenditures on health	1.029165	0.0098611	3	0.003	(1.01, 1.05)	1.023285	0.0031902	7.38	0	(1.02, 1.03)
	External resources for health per capita	1.329672	0.0959552	3.95	0	(1.15, 1.53)	1.205292	0.020326	11.07	0	(1.17, 1.25)
	Land area	0.999959	0.0000124	-3.3	0.001	(1.00, 1,00)	0.9999704	2.80E-06	-10.57	0	(1,00, 1.00)
	Linguistic fractionalization	5.90E+22	1.07E+24	2.88	0.004	(1.95E+07, 1.78E+38)	6.95E+15	2.62E+16	9.69	0	(4.34E+12, 1.11E+19)
	Distance	0.2893782	0.1262367	-2.84	0.004	(0.12, 0.68)	0.3631924	0.0340301	-10.81	0	(0.30, 0.44)
	Integration	13.21398	53.10655	0.64	0.521	(0.005, 34832.43)	5.877308	2.791309	3.73	0	(2.32, 14.91)

		Table 14, Continued. Predictors of Group Membership: Geographic Equity									
		Non-Imputed Dataset					Imputed Dataset				
Group	Predictor of Group Membership	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval
5	Income	0.0001449	0.0009321	-1.37	0.169	(4.84E-10, 43.33)	0.0002009	0.0003293	-5.19	0	(8.08E-06, 0.005)
	Region	2.37E-06	0.0000125	-2.45	0.014	(7.49E-11, 0.075)	0.000014	0.0000156	-9.99	0	(1.56E-06, 0.0001)
	Female education	1.525957	0.28375	2.27	0.023	(1.06, 2.196961)	1.362198	0.0620816	6.78	0	(1.25, 1.49)
	Political stability	2064366	1.48E+07	2.03	0.043	(1.61, 2.65E+12)	59958.64	83404.48	7.91	0	(3924.66, 916013)
	Government effectiveness	6816403	5.80E+07	1.85	0.064	(0.39, 1.18E+14)	1431966	2782493	7.29	0	(31764.32, 6.46E+07)
	Corruption	0.0347788	0.1946669	-0.6	0.548	(5.98E-07, 2021.75)	0.3779067	0.4829463	-0.76	0.446	(0.031, 4.63)
	Gender inequality	9.55E+09	1.49E+11	1.47	0.141	(0.00050, 1.81E+23)	2.74E+08	8.95E+08	5.95	0	(456180.3, 1.65E+11)
	Out-of-pocket health expenditures	2.179092	0.6281979	2.7	0.007	(1.24, 3.83)	1.873801	0.1105773	10.64	0	(1.67, 2.10)
	Government expenditures on health	0.9757595	0.0173786	-1.38	0.168	(0.94, 1.010422)	0.9727223	0.0047124	-5.71	0	(0.96, 0.98)
	External resources for health per capita	1.04877	0.0802546	0.62	0.534	(0.90, 1.22)	1.040898	0.0198082	2.11	0.035	(1.00, 1.08)
	Land area	1.000016	7.67E-06	2.02	0.043	(1.00, 1.00)	1.000013	1.64E-06	7.87	0	(1.00, 1.00)
	Linguistic fractionalization	1.13E+23	2.11E+24	2.84	0.005	(1.33E+07, 9.61E+38)	9.93E+16	3.83E+17	10.15	0	(5.17E+13, 1.91E+20)
	Distance	0.361731	0.1553857	-2.37	0.018	(0.16, 0.84)	0.4262153	0.0395776	-9.18	0	(0.36, 0.51)
	Integration	1.393845	5.714739	0.08	0.935	(0.00045, 4306.50)	3.268299	1.624808	2.38	0.017	(1.23, 8.66)

		Table 15. Predictors of Group Membership: Socioeconomic Equity									
		Non-Imputed Dataset					Imputed Dataset				
Group	**Predictor of Group Membership**	**Relative Risk**	**Standard Error**	**z**	**P>|z|**	**95% Confidence Interval**	**Relative Risk**	**Standard Error**	**z**	**P>|z|**	**95% Confidence Interval**
1 (base outcome)											
2	**Income**	2.241445	1.979536	0.91	0.361	(0.40, 12.66)	5.307659	0.892067	9.93	0	(3.82, 7.38)
	Region	0.8764091	0.315655	-0.37	0.714	(0.43, 1.77)	1.088548	0.055033	1.68	0.093	(0.99, 1.20)
	Female education	0.9141557	0.020847	-3.94	0	(0.87, 0.96)	0.990228	0.003427	-2.84	0.005	(0.98, 1.00)
	Political stability	2.524515	1.381406	1.69	0.091	(0.86, 7.38)	1.27432	0.106547	2.9	0.004	(1.08, 1.50)
	Government effectiveness	1.342423	1.632695	0.24	0.809	(0.12, 14.56)	1.756637	0.406063	2.44	0.015	(1.12, 2.76)
	Corruption	0.1219006	0.151205	-1.7	0.09	(0.011, 1.39)	0.207852	0.045946	-7.11	0	(0.13, 0.32)
	Gender inequality	1.73E-06	4.04E-06	-5.68	0	(1.77E-08, 0.00017)	3.338941	0.946851	4.25	0	(1.92, 5.82)
	Out-of-pocket health expenditures	1.012023	0.019145	0.63	0.528	(0.98, 1.05)	0.960434	0.00386	-10.04	0	(0.95, 0.97)
	Government expenditures on health	0.9751033	0.007042	-3.49	0	(0.96, 0.99)	0.961332	0.002243	-16.9	0	(0.96, 0.97)
	External resources for health per capita	0.9015603	0.025435	-3.67	0	(0.85, 0.95)	0.974827	0.004079	-6.09	0	(0.97, 0.98)
	Land area	1.000006	1.23E-06	4.82	0	(1.00, 1.00)	1.000001	1.17E-07	10.96	0	(1.00, 1.00)
	Linguistic fractionalization	1.246866	1.505423	0.18	0.855	(0.12, 13.29)	2.272543	0.52127	3.58	0	(1.45, 3.56)
	Distance	1.018492	0.021547	0.87	0.386	(0.98, 1.06)	1.024245	0.003106	7.9	0	(1.02, 1.03)
	Integration	0.837396	0.802561	-0.19	0.853	(0.13, 5.48)	0.489647	0.062383	-5.6	0	(0.38, 0.63)

		Table 15, Continued. Predictors of Group Membership: Socioeconomic Equity									
		Non-Imputed Dataset					Imputed Dataset				
Group	Predictor of Group Membership	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval
3	Income	4.655903	3.987518	1.8	0.073	(0.87, 24.95)					
	Region	0.9844899	0.352523	-0.04	0.965	(0.49, 1.99)					
	Female education	0.9395753	0.018313	-3.2	0.001	(0.90, 0.98)					
	Political stability	1.540575	0.746975	0.89	0.373	(0.60, 3.98)					
	Government effectiveness	1.124743	1.387484	0.1	0.924	(0.10, 12.62)					
	Corruption	0.0858633	0.101331	-2.08	0.038	(0.0085, 0.87)					
	Gender inequality	0.000375	0.000822	-3.6	0	(5.10E-06, 0.028)					
	Out-of-pocket health expenditures	0.9496381	0.019364	-2.53	0.011	(0.91, 0.99)					
	Government expenditures on health	0.9457635	0.010652	-4.95	0	(0.93, 0.97)					
	External resources for health per capita	0.8876052	0.024401	-4.34	0	(0.84, 0.94)					
	Land area	1.000005	1.20E-06	4.58	0	(1.00, 1.00)					
	Linguistic fractionalization	17.64553	20.0658	2.52	0.012	(1.90, 163.90)					
	Distance	1.048426	0.020577	2.41	0.016	(1.01, 1.09)					
	Integration	0.4460937	0.417046	-0.86	0.388	(0.07, 2.79)					

		Table 15, Continued. Predictors of Group Membership: Socioeconomic Equity									
		Non-Imputed Dataset					Imputed Dataset				
Group	Predictor of Group Membership	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval	Relative Risk	Standard Error	z	P>|z|	95% Confidence Interval
4	Income	5.44E+19	5.22E+23	0	0.996	-					
	Region	3451.95	6698449	0	0.997	-					
	Female education	0.5746389	124.3169	0	0.998	(4.10E-185, 8.10E+183)					
	Political stability	0.4704951	2075.301	0	1	-					
	Government effectiveness	1.117109	11581.04	0	1	-					
	Corruption	0.0000242	0.167434	0	0.999	-					
	Gender inequality	0.1436708	3428.467	0	1	-					
	Out-of-pocket health expenditures	0.9852097	263.2934	0	1	(3.30E-228, 3.00E+227)					
	Government expenditures on health	1.00599	6.158619	0	0.999	(6.19E-06, 163532.6)					
	External resources for health per capita	0.7057309	332.4281	0	0.999	-					
	Land area	1.000039	0.004727	0.01	0.993	(0.99, 1.01)					
	Linguistic fractionalization	6.05E-18	4.25E-14	-0.01	0.995	-					
	Distance	0.403834	42.49988	-0.01	0.993	(1.06E-90, 1.54E+89)					
	Integration	1.52547	8606.309	0	1	-					

CONCLUSION

"Public health is a historically evolving system with its own agenda and preferred solutions to problems. The principle that things are the way they are because they got that way has to be applied to public health as well. Then we can see the ways in which the present pattern of knowledge and ignorance is not a spontaneous consequence of some problems being harder than others, but rather a consequence of intellectual choices encouraged by the fragmentation of disciplines and institutions, the structures of reward and recognition, the financing of research in order to find marketable commodities, and unacknowledged constraints on the investigations, conditions that are accepted as givens without question."

Richard Levins and Cynthia Lopez

“Toward an Ecosocial View of Health”

5.1 Summary of Findings

Applying both qualitative and quantitative methods, this dissertation examined a broad range of vaccination issues during and after outbreaks in LMICs, each corresponding to WHO’s continuum of pandemic phases. The three papers comprising this work have articulated considerations for vaccine delivery during outbreak response efforts, investigated emergent immunization challenges in post-outbreak contexts, and described longitudinal trends in vaccination equity.

Paper 1 (Chapter 2) analyzed findings from a scoping literature review and key informant interviews on last mile challenges in vaccine delivery and uptake during outbreaks and presented a descriptive conceptual framework organizing these challenges in terms of geography, epidemiology, target populations, and health system considerations. Within each of these four framings, we further collated findings into broad thematic categories – governance and leadership, surveillance, workforce, program implementation, vaccine confidence, and population immunity – and identified several cross-cutting themes, including funding, quality assurance, ethics, equity, and integration. The resultant conceptual framework presents a typology of critical last mile challenges and illustrates how they are distinct from vaccination challenges encountered during earlier phases of outbreak response. We concluded that this important subset of challenges merits continued scholarship and demands focused attention during routine epidemic planning efforts in LMICs and resource-deprived settings.

Paper 2 (Chapter 3) presented findings from a comparative case study analysis tracing the post-epidemic trajectories of routine immunization programs in Liberia and Haiti, highlighting barriers and facilitators of immunization program recovery in these settings. Drawing from the peer-reviewed and grey literature, quantitative databases, and key informant interviews, we constructed descriptive narratives for each case and used the Essential Public Health Services Framework to compare and contrast processes of health system recovery across both settings. We found that the legacies of colonialism powerfully shaped the health systems and post-epidemic landscapes of these countries, particularly with respect to immunization workforce retention, satisfaction, and compensation. In both Liberia and Haiti, deeply entrenched power asymmetries between national governments and external partners have been compounded by recurrent geopolitical crises and natural disasters, which have gutted immunization capacities and left populations vulnerable to epidemic threats. We also learned that embedding in-country expertise within outbreak response structures, respecting governmental autonomy and self-determination, aligning post-epidemic recovery plans and policies, and integrating response assets into systems for routine vaccination resulted in more equitable levels of national and sub-national immunization coverage.

Over the course of this investigation, integration emerged as an important consideration both in the context of last mile challenges and post-epidemic health system recovery. This finding was the impetus behind Paper 3 (Chapter 4), which presented a series of group-based trajectory models that illustrate longitudinal trends in geographic and socioeconomic vaccination equity across 78 LMICs that have ever received support from Gavi, the Vaccine Alliance. Group-based trajectory modeling is a latent class modeling technique that enabled us to group and describe countries exhibiting similar developmental equity trajectories. Using a WHO-recommended metric of integrated vaccine delivery and multiple imputation to handle missing health service coverage data, we discovered positive associations between integration and equity and identified several predictors of country membership in high-performing groups. Paper 3 concludes with reflections on improving measurement of both integration and equity, as well as the potential utility of group-based trajectory modeling in future health systems research.

5.2 Implications for Future Public Health Research, Policy, and Practice

Findings from each of the three studies in this dissertation have salient implications for health systems research, policymaking, and practice, particularly in the context of ongoing efforts to mitigate both emergent crises like COVID-19 and longstanding, vaccine-preventable threats like polio, measles, and seasonal influenza. The conceptual framework of last mile challenges from Paper 1, for example, could help inform vaccination strategies in countries experiencing resurgences of imported or circulating vaccine-derived poliovirus after previously being declared polio-free. Similarly, as COVID-19 vaccines become more widely available to populations in the Global South, this framework could also support advance planning to dismantle demand-side barriers to vaccine uptake, refine surveillance strategies, and address workforce challenges, among other last-mile considerations. Given that our study was largely taxonomic in nature, future studies might also build on our framework by applying a complex adaptive systems lens to articulate linkages, feedback loops, and causal pathways underpinning last mile challenges. A more expansive evidence base contextualizing last mile challenges in under-studied settings or with respect to a broader range of diseases might further support such analyses. This understanding, in turn, is essential to the success of ongoing and future infectious disease mitigation, elimination, and eradication efforts.

As with Paper 1, the findings from Paper 2 may be especially relevant amid the ongoing global response to COVID-19. This case study analysis described how historical power dynamics not only shaped pre- and post-epidemic routine immunization programs in Liberia and Haiti, but actively created vacuums of state capacity and autonomy that left these countries vulnerable to the threats of Ebola and cholera, respectively. While the findings from this study are not necessarily generalizable to every post-epidemic health system context, they may be transferrable to low- and middle-income settings characterized by limited horizontal and public sector capacities, a strong vertical health program presence, and a high degree of health system participation and influence from external donors and higher-income partners. Many LMICs are likely to experience longer COVID-19 recovery timelines, due in large part to inequitable vaccine distribution schemes amid severe disruptions to routine immunization programs. As such, decision-makers in these countries and their external partners ought to adopt more equitable, productive models of partnership and collaboration that do not reify colonial patterns of injustice in health system governance and health service delivery. The findings from this study highlight avoidable pitfalls and shed light on effective recovery practices – for example, policy alignment and country ownership of recovery efforts – that could guide policymakers and practitioners striving to rebuild or strengthen immunization programs derailed by COVID-19. Follow-on case studies might examine post-epidemic immunization programs in other countries to identify additional barriers and facilitators of recovery. Coupling other methodological frameworks, such as a positive deviance lens, with additional forms of data (e.g., social media content, financial data, mobile data) and methods of data collection (e.g., focus groups, community-based participatory research) could also provide insights into demand-side considerations for post-epidemic health system recovery.[302]

Paper 3 applied a quantitative method, group-based trajectory modeling, to describe vaccination equity in 78 LMICs and examine associations between integrated vaccine delivery and equity. GBTM, to our knowledge, has not been widely applied in health systems research but may have considerable utility as an exploratory method for describing complex longitudinal phenomena, particularly when randomized controlled trials or other experimental study designs are not possible. Our study shows that linking delivery of essential health services is associated with improved vaccination equity in settings with high baseline levels of inequity – a finding that could inform resource allocation and budgetary decisions in settings predominated by vertical immunization programs. This finding also aligns with calls to resume routine immunization activities in tandem with COVID-19 response efforts.[378] Paper 3 also discusses the limitations of current metrics of integration and proposes alternative measures that could improve monitoring and evaluation efforts around vaccination coverage and equity in LMICs. Our investigation also underscored a critical need for further scholarship around the determinants, drivers, and effects of integrated vaccine delivery. Future qualitative studies – such as case study analyses of countries that have achieved integration and successfully transitioned away from Gavi support – could help elucidate these factors, which might include varying health insurance schemes, planning and implementation processes, workforce structures, or levels of trust in public health and medical institutions.[316] Given that our study identified positive associations between integration and equity, future quantitative analyses might also consider alternative options for ascertaining potential causal relationships between the two.

5.3 Final Reflections

Though each study in this investigation examined a different facet of vaccination at varying stages of outbreak response and recovery, all three coalesce around a single unifying theme: the imperative to achieve and sustain high levels of equitable immunization coverage, mediated by integrating vaccination capacities into robust systems of care. With respect to systems integration, Margaret J. Wheatley and Myron Kellner-Rogers write:

> "To create better health in a living system, connect it to more of itself. When a system is failing, or performing poorly, the solution will be discovered within the system if more and better connections are created. A failing system needs to start talking to itself, especially to those it didn't know were even part of itself…This principle embodies a profound respect for systems. It says that they are capable of changing themselves, once they are provided with new and richer information. It says that they have a natural tendency to move toward better functioning or health. It assumes that the system already has within it most of the expertise that it needs. This principle also implies that the critical task for a leader is to increase the number, variety and strength of connections within the system."[379]

Contextualizing this principle in global public health research and practice, the health systems scholar Ṣẹ̀yẹ Abímbọ́lá further asserts, “In thinking that our primary role is to produce new knowledge rather than helping to connect a system, any system, to more of itself, we have been unjust.”[380] Thus, for the full range of life course benefits associated with equitable immunization to be realized, the systemic components that successful vaccine delivery demands – technical and tacit knowledge, competent workforces, and requisite levels of social, economic, and political capital – must be in resonance with one another.

By synthesizing previous scholarship, key informant expertise, and secondary data to describe challenges in last mile vaccine delivery, analyze post-epidemic immunization program recovery, and highlight associations between integration and equity, this dissertation advocates for forging stronger linkages between these systemic components. In terms of public health practice, strengthening such linkages requires continuous assessment of whether needed system inputs are in place, whether existing mechanisms of collaboration and engagement are sufficiently equipped to dismantle barriers to equitable vaccine access, and perhaps most importantly, in whose interest the system in question is functioning. Ultimately, by actively pursuing requisite structural transformations to improve vaccination integration, delivery, and equity, researchers, practitioners, and decision-makers can strengthen public health preparedness and safeguard population health.

Appendix A

Scoping Literature Review Search Strategy

Peer-Reviewed Literature Databases	Search Terms
PubMed (National Library of Medicine)	▪ (implementation science[MeSH Terms]) AND immunization[MeSH Terms] ▪ (((((((disease outbreak[MeSH Terms]) AND immunization[MeSH Terms]) AND delivery of healthcare AND Humans[Mesh])) AND (barriers OR considerations OR impediment OR obstacle OR stumbling block OR last mile OR implementation OR distribution OR delivery OR dispense OR dispersal)) AND Humans[Mesh])) NOT delivery, obstetric[MeSH Terms] ▪ vaccine AND endgame AND outbreak
Embase (Elsevier)	▪ immunization AND (recommendations OR obstacles) AND ('last mile' OR 'health care delivery' OR implementation OR 'implementation science') AND [humans]/lim AND [english]/lim AND ('article'/it OR 'article in press'/it OR 'chapter'/it OR 'conference paper'/it OR 'editorial'/it OR 'letter'/it OR 'review'/it OR 'short survey'/it)
Scopus (Elsevier)	▪ "last mile" AND immunization OR vaccine ▪ vaccine AND endgame AND outbreak
PsycINFO (American Psychological Association)	▪ "last mile" ▪ "last mile" AND challenges ▪ "last mile challenges" ▪ "last mile" AND vaccine OR vaccination ▪ vaccine AND endgame AND outbreak
Cumulative Index to Nursing & Allied Health Literature (EBSCO)	
Grey Literature Databases	**Search Terms**
ReliefWeb	▪ last mile AND vaccine ▪ (vaccinate OR vaccine OR vaccination OR immunise OR immunize OR immunization OR immunisation) AND (recommendation OR problem OR issue OR barriers OR considerations OR impediment OR obstacle OR stumbling block) AND (last mile OR implementation OR distribution OR delivery OR dispense OR dispersal) ▪ vaccine AND endgame AND outbreak
OpenGrey (INIST-CNRS)	

<table>
<tr><td>CDC Stacks</td><td rowspan="5">▪ “last mile”
▪ “last mile” AND challenges
▪ “last mile challenges”
▪ “last mile” AND vaccine OR vaccination
vaccine AND endgame AND outbreak</td></tr>
<tr><td>Health Systems Evidence (McMaster Health Forum)</td></tr>
<tr><td>Global Index Medicus (World Health Organization)</td></tr>
<tr><td>LILACS (Pan American Health Organization)</td></tr>
<tr><td>Think Tank Search (Harvard Kennedy School)</td></tr>
</table>

Exclusion criteria:

- Non-English-language articles

- Irrelevance (based on title and abstract review; i.e., document does not address last mile challenges in public health and/or vaccine delivery)

Appendix B

Key Informant Semi-Structured Interview Protocol

1. Please describe your involvement in responding to the [Ebola/cholera] epidemic in [Liberia/Haiti].

2. Please describe how your organization coordinated with other NGOs, responding agencies, and government agencies operating in [Liberia/Haiti] during this time.

3. Tell us what routine immunization activities and programs in [Liberia/Haiti] looked like immediately after the [Civil War/earthquake]. Were there major disruptions?

    a. What about after the [Ebola/cholera] epidemic took off?
    b. Were there some parts of the country that experienced more disruptions in routine immunization than others?

4. **Assessment:**

    a. Please describe whether or how surveillance for vaccine-preventable diseases changed after the [Ebola/cholera] epidemic took off.
    b. Were there concerns about seeing a spike in cases of vaccine-preventable diseases? What plans were in place to deal with those, if so?

5. **Policy Development:**

    a. Can you provide examples of community engagement efforts around routine vaccination during and after the [Ebola/cholera] epidemic?
    b. Were there specific risk communication strategies or community partnerships that your team relied on to help promote routine vaccination?
    c. Were there national laws, policies, or other government directives that supported routine immunization during this time?

6. **Assurance:**

    a. How were resources for routine immunization distributed across [counties, districts, departments, and/or *arondissements*]?
    b. Were there efforts made to strengthen [Liberia/Haiti]'s domestic immunization workforce during this time?
    c. What other steps were taken to strengthen [Liberia/Haiti]'s health system during this time?

7. If you could change any aspect of how your organization responded to the crisis in [Liberia/Haiti], what would you change?

Appendix C

Characteristics of Key Informants Interviewed (Case Study Analysis)

#	Discipline & Issue Expertise	Professional Domain‡‡‡			Geographic Focus	
		In-Country Government	External Donor or Partner	Civil Society	Liberia	Haiti
KI1	Public health: project management, sustainability, health system governance		✓	✓		✓
KI2	Public health: immunization, surveillance for vaccine-preventable diseases		✓			✓
KI3	Public health: maternal & child health, cholera, monitoring & evaluation		✓			✓
KI4	Humanitarian health: cholera, emergency response, program evaluation		✓			✓
KI5	Humanitarian health: program coordination, immunization microplanning, outbreak response		✓	✓		✓
KI6	Health financing: policy, costing of health services, budget management		✓			✓
KI7	Public health: primary health care, capacity-building, health advocacy			✓		✓

‡‡‡ In several cases, key informants reported serving across multiple professional domains over the course of their work in Haiti and/or Liberia.

#	Discipline & Issue Expertise	Professional Domain			Geographic Focus	
		In-Country Government	External Donor or Partner	Civil Society	Liberia	Haiti
KI8	Public health: routine immunization		✓			✓
KI9	Public health: routine immunization, vaccine introduction, surveillance	✓				✓
KI10	Public health & medicine: primary care, women's health, health workforce training			✓		✓
KI11	Public health: epidemiology, monitoring & evaluation			✓	✓	
KI12	Public health: routine immunization, epidemiology, surveillance			✓	✓	
KI13	Public health: demography, incident management, outbreak response	✓			✓	
KI14	Policy: peacebuilding, health governance	✓		✓	✓	
KI15	Public health: routine immunization	✓		✓	✓	
KI16	Public health: routine immunization	✓		✓	✓	
KI17	Public health: routine immunization, epidemiology, child health, medicine			✓	✓	
KI18	Public health: routine immunization, health systems strengthening	✓		✓	✓	

#	Discipline & Issue Expertise	Professional Domain			Geographic Focus	
		In-Country Government	External Donor or Partner	Civil Society	Liberia	Haiti
KI19	Public health: community engagement, risk communication	✓			✓	
KI20	Public health: epidemiology, outbreak response, surveillance	✓			✓	
KI21	Public health: incident management, outbreak response, health systems strengthening	✓			✓	

Appendix D

Group-Based Trajectory Model Data Glossary

Descriptive Indicators	Description	Type	Data Source
Alpha-3 code	Standardized 3-letter country codes designated by the International Organization for Standardization	Alphanumeric	ISO Alpha-3 codes
Independent Variables	**Description**	**Type**	**Data Source**
Antenatal care coverage	National coverage of at least one antenatal care visit (%)	Continuous	Demographic and Health Surveys (DHS) & Multiple Indicator Cluster Surveys (MICS)
Control of corruption	Measurement of perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests	Continuous	Worldwide Governance Indicators
Diphtheria-tetanus-pertussis vaccination coverage	National coverage of the third dose of diphtheria-tetanus-pertussis-containing vaccine (%)	Continuous	WHO-UNICEF Joint Reporting Forms on Immunization
Distance to the nearest health facility	Proportion of the population more than 60 minutes away (by walking) from the nearest health facility (%)	Continuous	Weiss et al. ("Global maps of travel time to healthcare facilities," *Nature Medicine*)
External resources for health per capita	External resources for health per capita (expressed in current international dollars, purchasing power parity)	Continuous	WHO Global Health Expenditure Database

Independent Variables	Description	Type	Data Source
Gender inequality index	A composite measure reflecting inequality in achievement between women and men in three dimensions: reproductive health, empowerment and the labor market	Continuous	United Nations Development Programme Human Development Reports
Government effectiveness	Measurement of perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies	Continuous	Worldwide Governance Indicators
Government expenditure on health per capita	Government health expenditures (in current international dollars, purchasing power parity)	Continuous	WHO Global Health Expenditure Database
Income Level	World Bank Region	Alphanumeric	▪ World Bank Country and Lending Groups
Integrated vaccine delivery	This analysis utilizes the dichotomous measure developed by the WHO SAGE working group and adopted by Gavi, wherein countries are considered to have achieved integration only if national co-coverage levels of MCV1, DTP3, PAB, and ANC1 exceed 70%, and are within 10 percentage points of one another.	Dichotomous	▪ WHO-UNICEF Joint Reporting Forms on Immunization ▪ WHO Global Health Observatory ▪ Demographic and Health Surveys (DHS) & Multiple Indicator Cluster Surveys (MICS)

Independent Variables	Description	Type	Data Source
Land area	National land area (square kilometers)	Continuous	World Bank Open Data
Linguistic fractionalization	A measure of linguistic diversity within a given country	Continuous	Alesina et al. ("Fractionalization," *Journal of Economic Growth*)
Measles vaccination coverage	National coverage of the first dose of measles-containing vaccine (%)	Continuous	WHO-UNICEF Joint Reporting Forms on Immunization
Measles vaccination coverage in the wealthiest quintile	National coverage of the first dose of measles-containing vaccine in the wealthiest quintile (%)	Continuous	Demographic and Health Surveys (DHS) & Multiple Indicator Cluster Surveys (MICS)
Measles vaccination coverage in the poorest quintile	National coverage of the first dose of measles-containing vaccine in the poorest quintile (%)	Continuous	Demographic and Health Surveys (DHS) & Multiple Indicator Cluster Surveys (MICS)
Out-of-pocket expenditure on health	Share of out-of-pocket expenditure on health (as a percentage of total health expenditure)	Continuous	WHO Global Health Expenditure Database
Political stability and absence of violence and terrorism	Measurement of the likelihood of political instability and/or politically motivated violence, including terrorism	Continuous	Worldwide Governance Indicators
Protection at birth against neonatal tetanus	National proportion of neonates protected at birth against neonatal tetanus via maternal immunization (%)	Continuous	WHO Global Health Observatory
Region	Current income level (as of 2022, per the World Bank)	Alphanumeric	World Bank Country and Lending Groups
Women with completed primary education	National proportion of women who have completed their primary education	Continuous	World Development Indicator Database

Dependent Variables	Description	Type	Data Source
Geographic vaccination equity	Proportion of districts reporting ≥ 80% coverage of measles-containing vaccine	Continuous	WHO-UNICEF Joint Reporting Forms on Immunization
Socioeconomic vaccination equity	Slope index of inequality (SII) based on MCV1 coverage disaggregated by wealth quintile	Continuous	Demographic and Health Surveys (DHS) & Multiple Indicator Cluster Surveys (MICS)

APPENDIX E

Group-Based Trajectory Model
Geographic Equity (Non-Imputed)

```
*Install the traj plugin.*
net from https://www.andrew.cmu.edu/user/bjones/traj
net install traj
help traj

log using gbtmgeo

import delimited "[redacted]Integrated Vaccine Delivery & Equity.csv" /// Import dataset.

*Assign labels to each variable in the dataset.*

label variable alpha3 "Alpha-3 Code"
label variable region "World Bank Region"
label variable income "Income Level"
label variable q5coverage "MCV1 Coverage in the Wealthiest Quintile"
label variable q4coverage "MCV1 Coverage in the 4th Quintile"
label variable q3coverage "MCV1 Coverage in the 3rd Quintile"
label variable q2coverage "MCV1 Coverage in the 2nd Quintile"
label variable q1coverage "MCV1 Coverage in the Poorest Quintile"
label variable geoequity "Geographic Equity"
label variable sii "Slope Index of Inequality"
label variable dtp3 "DTP3 Coverage"
label variable mcv1 "MCV1 Coverage"
label variable anc1 "Antenatal Care Coverage (1+ Visits)"
label variable pab "Protection at Birth Against Neonatal Tetanus"
label variable femeduc "Female Primary Education Completed"
label variable polstability "Political Stability"
label variable goveffect "Government Effectiveness"
label variable corrupt "Corruption"
label variable gii "Gender Inequality Index"
label variable oopexp "Out-of-Pocket Health Expenditures"
label variable govexp "Domestic Government Health Expenditures"
label variable exthlth "External Health Spending"
label variable land "Land Area"
label variable lingfrac "Linguistic Fractionalization"
label variable distance "Distance to Nearest Health Facility (Walking, 60+ Minutes)"
```

```
***************************************************************
          Creating new variables for integrated vaccine delivery + miscellaneous.
***************************************************************

generate integration = 0
label variable integration "Integrated Vaccine Delivery"

*Create new variables representing all possible absolute differences between MCV1,
DTP3, ANC1, and PAB coverage levels.*

generate abs_mcv1dtp3 = abs(mcv1-dtp3)
generate abs_mcv1anc1 = abs(mcv1-anc1)
generate abs_mcv1pab = abs(mcv1-pab)
generate abs_dtp3anc1 = abs(dtp3-anc1)
generate abs_dtp3pab = abs(dtp3-pab)
generate abs_anc1pab = abs(anc1-pab)

*Set "integration" to 1 if coverage of all four services (MCV1, DTP3, ANC1, PAB) is
greater than or equal to 70%, and all four are within 10 percentage points of one
another.*

replace integration = 1 if mcv1>=70 & dtp3>=70 & anc1>=70 & pab>=70 &
abs_mcv1dtp3<=10 & abs_mcv1anc1<=10 & abs_mcv1pab<=10 & abs_dtp3anc1<=10
& abs_dtp3pab<=10 & abs_anc1pab<=10

*Create a table summarizing events (i.e., "integration" = 1) by country.*

tabulate country integration

*Create a new variable ("year_dup") that duplicates the "Year" column of the dataset.*

generate year_dup = year

*Encode alpha3, region, and income (string variables) as numeric variables "numid,"
"region2," and "income2."*

encode alpha3, generate(numid)
sort numid

encode region, generate(region2)

encode income, generate(income2)
```

Drop observations before 2008.

```
drop if year < 2008
```

****
Group-based trajectory analysis for geographic equity
****

Reshape the dataset from long to wide format; wide format is required to run the traj Stata plugin.

```
reshape wide country region region2 income income2 alpha3 q5coverage q4coverage
q3coverage q2coverage q1coverage geoequity sii dtp3 mcv1 anc1 pab femeduc
polstability goveffect corrupt gii oopexp govexp exthlth land lingfrac distance
abs_mcv1dtp3 abs_mcv1anc1 abs_mcv1pab abs_dtp3anc1 abs_dtp3pab abs_anc1pab
integration year_dup, i(numid) j(year)
```

Run the traj plugin using a censored normal model, with "year_dup" as the independent variable and "geoequity" as the outcome of interest. The censored normal distribution ("cnorm") model is specified because geoequity is a repeatedly measured, continuous outcome censored by minimum and maximum values.

Run the plugin several times, changing only the number of groups specified ("order") and holding all other parameters constant. Select the model/group number that produces the highest BIC value.

```
traj, model(cnorm) var(geoequity*) indep(year_dup*) min(0) max(110) order(0 0)
traj, model(cnorm) var(geoequity*) indep(year_dup*) min(0) max(110) order(0 0 0)
traj, model(cnorm) var(geoequity*) indep(year_dup*) min(0) max(110) order(0 0 0 0)
traj, model(cnorm) var(geoequity*) indep(year_dup*) min(0) max(110) order(0 0 0 0 0)
```

The five-group model produced a high BIC value, so we will move forward with this option. Next, toggle the polynomial order for each group to achieve the largest possible BIC. The model below represents the tested option with the highest BIC value. The "detail" command generates parameter estimates that will be used to calculate confidence intervals in a later step.

```
traj, model(cnorm) var(geoequity*) indep(year_dup*) min(0) max(110) order(1 1 1 1 1)
tcov(integration*) detail
```

Plot the trajectories for the two groups, along with accompanying confidence intervals. Assessing the confidence intervals provides an additional diagnostic check for the model (i.e., narrower, non-overlapping CIs are preferred).

```
trajplot, xtitle("Year") ytitle("Geographic Equity (%)") xlabel(2008(2)2020) ci
```

Perform parametric bootstrap sampling to estimate group size confidence intervals. Use parameter estimates from the traj output as the starting values for the matrix command.

```
matrix strt = -3726.42195, 1.86395, -7.70874, 2864.77166, -1.39961, 9.00932, 8.81971,
0.03398, 3.87270, -368.32445, 0.23072, 1.75297, -6808.17372, 3.40992, -5.38055,
14.68529, 13.03584, 17.61859, 27.05399, 29.67699, 12.61459

bootstrap _b (100/(1+exp(_b[theta2]))) (100*exp(_b[theta2])/(1+exp(_b[theta2]))),
reps(1000) dots(10): traj, model(cnorm) var(geoequity*) indep(year_dup*) min(-1000)
max(1000) order(1 1 1 1 1) tcov(integration*) start(strt) novar

estat bootstrap, percentile bc
```

Create a program, "trajstats," to calculate several other diagnostic criteria for group-based trajectory models.

```
program trajstats

preserve
```

This step calculates the average posterior probability.

```
generate Mp=0

foreach i of varlist _traj_ProbG* {
            replace Mp = `i' if `i' > Mp
        }
   sort _traj_Group

by _traj_Group: generate countG = _N
```

This step calculates the odds of correct classification.

```
   by _traj_Group: egen groupAPP = mean(Mp)
   by _traj_Group: generate counter = _n
   generate n = groupAPP/(1 - groupAPP)
```

```
   generate p = countG/ _N
   generate d = p/(1-p)
   generate occ = n/d
```

This step calculates the estimated group probabilities vs. the proportion of the sample assigned to the group.

```
        scalar c = 0
   gen TotProb = 0
   foreach i of varlist _traj_ProbG* {
     scalar c = c + 1
     quietly summarize `i'
     replace TotProb = r(sum)/ _N if _traj_Group == c
   }
        gen d_pp = TotProb/(1 - TotProb)
        gen occ_pp = n/d_pp
```

*This step displays:
*Group number [_traj_~p],
*Count per group (based on the max post prob), [countG]
*Average posterior probability for each group, [groupAPP]
*Odds of correct classification (based on the maximum posterior group assignment rule), [occ]
*Odds of correct classification (based on the weighted posterior probabilities), [occ_pp]
Observed probability of groups [p] versus the probability based on the posterior probabilities [TotProb]

```
list _traj_Group countG groupAPP occ occ_pp p TotProb if counter == 1

restore

end
```

Now, run the trajstats program.

```
trajstats
```

Create a list of group assignments and group membership probabilities for all subjects.

```
list _traj_Group - _traj_ProbG5
```

Reshape the dataset from wide to long format.

```
reshape long
```

Perform multinomial logistic regression to identify covariates with statistically significant associations with group membership, setting Group 1 membership as the base outcome. Save results.

```
drop if year < 2003

mlogit _traj_Group income2 region2 femeduc polstability goveffect corrupt gii oopexp govexp exthlth land lingfrac distance integration, baseoutcome(1) rrr
```

****
Close log and save as PDF
****

```
log close

translate gbtmgeo.smcl gbtmgeo.pdf
```

APPENDIX F

Group-Based Trajectory Model
Geographic Equity (Imputed)

```
*Install the traj package.*
net from https://www.andrew.cmu.edu/user/bjones/traj
net install traj
help traj

log using migbtmgeo

*Import dataset.*

import delimited "[redacted]Integrated Vaccine Delivery & Equity.csv"

*Assign labels to each variable in the dataset.*

label variable alpha3 "Alpha-3 Code"
label variable region "World Bank Region"
label variable income "Income Level"
label variable q5coverage "MCV1 Coverage in the Wealthiest Quintile"
label variable q4coverage "MCV1 Coverage in the 4th Quintile"
label variable q3coverage "MCV1 Coverage in the 3rd Quintile"
label variable q2coverage "MCV1 Coverage in the 2nd Quintile"
label variable q1coverage "MCV1 Coverage in the Poorest Quintile"
label variable geoequity "Geographic Equity"
label variable sii "Slope Index of Inequality"
label variable dtp3 "DTP3 Coverage"
label variable mcv1 "MCV1 Coverage"
label variable anc1 "Antenatal Care Coverage (1+ Visits)"
label variable pab "Protection at Birth Against Neonatal Tetanus"
label variable femeduc "Female Primary Education Completed"
label variable polstability "Political Stability"
label variable goveffect "Government Effectiveness"
label variable corrupt "Corruption"
label variable gii "Gender Inequality Index"
label variable oopexp "Out-of-Pocket Health Expenditures"
label variable govexp "Domestic Government Health Expenditures"
label variable exthlth "External Health Spending"
label variable land "Land Area"
label variable lingfrac "Linguistic Fractionalization"
```

```
label variable distance "Distance to Nearest Health Facility (Walking, 60+ Minutes)"

*********************************************************
***Perform multiple imputation to handle missing data***
*********************************************************

*First, identify missing values in the dataset. Install the "mdesc" package if needed.*

mdesc q5coverage q4coverage q3coverage q2coverage q1coverage geoequity sii dtp3
mcv1 anc1 pab femeduc polstability goveffect corrupt gii oopexp govexp exthlth land
lingfrac distance

*Create a pairwise correlation matrix to identify potential auxiliary variables.*

pwcorr q5coverage q4coverage q3coverage q2coverage q1coverage geoequity sii dtp3
mcv1 anc1 pab femeduc polstability goveffect corrupt gii oopexp govexp exthlth land
lingfrac distance

*Set the data for multiple imputation. The "mi set mlong" command generates three
additional variables that Stata will use to track the imputed datasets and values.*

mi set flong

*Summarize missing values in the dataset.*

mi misstable summarize q5coverage q4coverage q3coverage q2coverage q1coverage
geoequity sii dtp3 mcv1 anc1 pab femeduc polstability goveffect corrupt gii oopexp
govexp exthlth land lingfrac distance

*Summarize missing patterns in the dataset.*

mi misstable patterns q5coverage q4coverage q3coverage q2coverage q1coverage
geoequity sii dtp3 mcv1 anc1 pab femeduc polstability goveffect corrupt gii oopexp
govexp exthlth land lingfrac distance

*Register the variables to be imputed.*

mi register imputed q5coverage q4coverage q3coverage q2coverage q1coverage
geoequity sii anc1 pab

*Specify the imputed model.*

mi impute mvn geoequity anc1 pab = mcv1, add(10) rseed(54321) force
```

```
*Specify a linear regression model to estimate the missing values. esample(imputed) creates a new variable, "imputed," that equals 1 for observations that are used in the imputation and 0 otherwise.*

mi estimate, esample(imputed): regress q5coverage q4coverage q3coverage q2coverage q1coverage sii geoequity anc1 pab

*Create a table of observations not used in the imputation model.*

tabulate country year if imputed == 0

*Perform a diagnostic check to assess how well the imputation was performed; check inflation of standard errors.*

mi estimate, vartable dftable

drop imputed

***************************************************************Creating new variables for integrated vaccine delivery + miscellaneous.
***************************************************************

generate integration = 0
label variable integration "Integrated Vaccine Delivery"

*Create new variables representing all possible absolute differences between MCV1, DTP3, ANC1, and PAB coverage levels.*

generate abs_mcv1dtp3 = abs(mcv1-dtp3)
generate abs_mcv1anc1 = abs(mcv1-anc1)
generate abs_mcv1pab = abs(mcv1-pab)
generate abs_dtp3anc1 = abs(dtp3-anc1)
generate abs_dtp3pab = abs(dtp3-pab)
generate abs_anc1pab = abs(anc1-pab)

*Set "integration" to 1 if coverage of all four services (MCV1, DTP3, ANC1, PAB) is greater than or equal to 70%, and all four are within 10 percentage points of one another.*

replace integration = 1 if mcv1>=70 & dtp3>=70 & anc1>=70 & pab>=70 & abs_mcv1dtp3<=10 & abs_mcv1anc1<=10 & abs_mcv1pab<=10 & abs_dtp3anc1<=10 & abs_dtp3pab<=10 & abs_anc1pab<=10
```

```
*Create a table summarizing events (i.e., "integration" = 1) by country."

tabulate country integration

*Create a new variable ("year_dup") that duplicates the "Year" column of the dataset.*

generate year_dup = year

*Encode alpha3, region, and income (string variables) as numeric variables "numid,"
"region2," and "income2."*

encode alpha3, generate(numid)
sort numid

encode region, generate(region2)

encode income, generate(income2)

drop if year < 2008

***********************************************************
***Group-based trajectory analysis for geographic equity***
***********************************************************

*Reshape the dataset from long to wide format; wide format is required to run the traj
Stata plugin.*

mi reshape wide country region region2 income income2 alpha3 q5coverage
q4coverage q3coverage q2coverage q1coverage geoequity sii dtp3 mcv1 anc1 pab
femeduc polstability goveffect corrupt gii oopexp govexp exthlth land lingfrac distance
abs_mcv1dtp3 abs_mcv1anc1 abs_mcv1pab abs_dtp3anc1 abs_dtp3pab abs_anc1pab
integration year_dup, i(numid) j(year)

*Run the traj plugin using a censored normal model, with "year_dup" as the
independent variable and "geoequity" as the outcome of interest. The censored normal
distribution ("cnorm") model is specified because geoequity is a repeatedly measured,
continuous outcome censored by minimum and maximum values.*

*Run the plugin several times, changing only the number of groups specified ("order")
and holding all other parameters constant. Select the model/group number that
produces the highest BIC value.*
```

```
traj, model(cnorm) var(geoequity*) indep(year_dup*) min(-200) max(200) order(0 0)
traj, model(cnorm) var(geoequity*) indep(year_dup*) min(-200) max(200) order(0 0 0)
traj, model(cnorm) var(geoequity*) indep(year_dup*) min(-200) max(200) order(0 0 0 0)

*Next, toggle the polynomial order for each group to achieve the largest possible BIC. The model below represents the tested option with the highest BIC value. The "detail" command generates parameter estimates that will be used to calculate confidence intervals in a later step.*

traj, model(cnorm) var(geoequity*) indep(year_dup*) min(-200) max(200) order(1 1 1 1 1) tcov(integration*) detail

*Plot the trajectories for the two groups, along with accompanying confidence intervals. Assessing the confidence intervals provides an additional diagnostic check for the model (i.e., narrower, non-overlapping CIs are preferred).*

trajplot, xtitle("Year") ytitle("Geographic Equity (%)") xlabel(2008(2)2020) ci

*Perform parametric bootstrap sampling to estimate group size confidence intervals. Use parameter estimates from the traj output as the starting values for the matrix command.*

matrix strt = -3828.30241, 1.91447, 8.31742, 3404.91985, -1.66889, 7.89603, 40.05184, 0.01830, 4.59730, -498.03972, 0.29490, 1.57810, -5519.40984, 2.76991, 1.71893, 15.83307, 12.07282, 17.44924, 26.44174, 28.23482, 15.80138

bootstrap _b (100/(1+exp(_b[theta2]))) (100*exp(_b[theta2])/(1+exp(_b[theta2]))), reps(1000) dots(10): traj, model(cnorm) var(geoequity*) indep(year_dup*) min(-1000) max(1000) order(1 1 1 1 1) tcov(integration*) start(strt) novar

estat bootstrap, percentile bc

*Create a program, "trajstats," to calculate several other diagnostic criteria for group-based trajectory models.*

program trajstats

preserve

*This step calculates the average posterior probability.*

generate Mp=0
```

```
foreach i of varlist _traj_ProbG* {
            replace Mp = `i' if `i' > Mp
        }
   sort _traj_Group

by _traj_Group: generate countG = _N

*This step calculates the odds of correct classification.*

   by _traj_Group: egen groupAPP = mean(Mp)
   by _traj_Group: generate counter = _n
   generate n = groupAPP/(1 - groupAPP)
   generate p = countG/ _N
   generate d = p/(1-p)
   generate occ = n/d

*This step calculates the estimated group probabilities vs. the proportion of the sample
assigned to the group.*

        scalar c = 0
   gen TotProb = 0
   foreach i of varlist _traj_ProbG* {
     scalar c = c + 1
     quietly summarize `i'
     replace TotProb = r(sum)/ _N if _traj_Group == c
   }
        gen d_pp = TotProb/(1 - TotProb)
        gen occ_pp = n/d_pp

 *This step displays:
   *Group number [_traj_~p],
   *Count per group (based on the max post prob), [countG]
   *Average posterior probability for each group, [groupAPP]
   *Odds of correct classification (based on the maximum
        posterior group assignment rule), [occ]
      *Odds of correct classification (based on the weighted posterior probabilities),
      [occ_pp]
      *Observed probability of groups [p] versus the probability based on the posterior
      probabilities [TotProb]*

list _traj_Group countG groupAPP occ occ_pp p TotProb if counter == 1

restore
```

```
end

*Now, run the trajstats program.*

trajstats

*Create a list of group assignments and group membership probabilities for all
subjects.*

list _traj_Group - _traj_ProbG2

*Reshape the dataset from wide to long format.*

mi reshape long country region region2 income income2 alpha3 q5coverage
q4coverage q3coverage q2coverage q1coverage geoequity sii dtp3 mcv1 anc1 pab
femeduc polstability goveffect corrupt gii oopexp govexp exthlth land lingfrac distance
abs_mcv1dtp3 abs_mcv1anc1 abs_mcv1pab abs_dtp3anc1 abs_dtp3pab abs_anc1pab
integration year_dup, i(numid) j(year)

*Perform multinomial logistic regression to identify covariates with statistically significant
associations with group membership, setting Group 1 membership as the base
outcome.*

drop if year < 2003

mlogit _traj_Group income2 region2 femeduc polstability goveffect corrupt gii oopexp
govexp exthlth land lingfrac distance integration, baseoutcome(1) rrr

******************************
***Close log and save as PDF***
******************************

log close

translate migbtmgeo.smcl migbtmgeo.pdf
```

APPENDIX G

Group-Based Trajectory Model
Socioeconomic Equity (Non-Imputed)

```
*Install the traj plugin.*
net from https://www.andrew.cmu.edu/user/bjones/traj
net install traj
help traj

log using gbtmsoc

import delimited "[redacted]Integrated Vaccine Delivery & Equity.csv" /// Import dataset.

*Assign labels to each variable in the dataset.*

label variable alpha3 "Alpha-3 Code"
label variable region "World Bank Region"
label variable income "Income Level"
label variable q5coverage "MCV1 Coverage in the Wealthiest Quintile"
label variable q4coverage "MCV1 Coverage in the 4th Quintile"
label variable q3coverage "MCV1 Coverage in the 3rd Quintile"
label variable q2coverage "MCV1 Coverage in the 2nd Quintile"
label variable q1coverage "MCV1 Coverage in the Poorest Quintile"
label variable geoequity "Geographic Equity"
label variable sii "Slope Index of Inequality"
label variable dtp3 "DTP3 Coverage"
label variable mcv1 "MCV1 Coverage"
label variable anc1 "Antenatal Care Coverage (1+ Visits)"
label variable pab "Protection at Birth Against Neonatal Tetanus"
label variable femeduc "Female Primary Education Completed"
label variable polstability "Political Stability"
label variable goveffect "Government Effectiveness"
label variable corrupt "Corruption"
label variable gii "Gender Inequality Index"
label variable oopexp "Out-of-Pocket Health Expenditures"
label variable govexp "Domestic Government Health Expenditures"
label variable exthlth "External Health Spending"
label variable land "Land Area"
label variable lingfrac "Linguistic Fractionalization"
label variable distance "Distance to Nearest Health Facility (Walking, 60+ Minutes)"
```

```
****************************************************************
          Creating new variables for integrated vaccine delivery + miscellaneous.
****************************************************************

generate integration = 0
label variable integration "Integrated Vaccine Delivery"

*Create new variables representing all possible absolute differences between MCV1,
DTP3, ANC1, and PAB coverage levels.*

generate abs_mcv1dtp3 = abs(mcv1-dtp3)
generate abs_mcv1anc1 = abs(mcv1-anc1)
generate abs_mcv1pab = abs(mcv1-pab)
generate abs_dtp3anc1 = abs(dtp3-anc1)
generate abs_dtp3pab = abs(dtp3-pab)
generate abs_anc1pab = abs(anc1-pab)

*Set "integration" to 1 if coverage of all four services (MCV1, DTP3, ANC1, PAB) is
greater than or equal to 70%, and all four are within 10 percentage points of one
another.*

replace integration = 1 if mcv1>=70 & dtp3>=70 & anc1>=70 & pab>=70 &
abs_mcv1dtp3<=10 & abs_mcv1anc1<=10 & abs_mcv1pab<=10 & abs_dtp3anc1<=10
& abs_dtp3pab<=10 & abs_anc1pab<=10

*Create a table summarizing events (i.e., "integration" = 1) by country."

tabulate country integration

*Create a new variable ("year_dup") that duplicates the "Year" column of the dataset.*

generate year_dup = year

*Encode alpha3, region, and income (string variables) as numeric variables "numid,"
"region2," and "income2."*

encode alpha3, generate(numid)
sort numid

encode region, generate(region2)

encode income, generate(income2)
```

****
Group-based trajectory analysis for socioeconomic equity
****

Reshape the dataset from long to wide format; wide format is required to run the traj Stata plugin.

```
reshape wide country region region2 income income2 alpha3 q5coverage q4coverage
q3coverage q2coverage q1coverage geoequity sii dtp3 mcv1 anc1 pab femeduc
polstability goveffect corrupt gii oopexp govexp exthlth land lingfrac distance
abs_mcv1dtp3 abs_mcv1anc1 abs_mcv1pab abs_dtp3anc1 abs_dtp3pab abs_anc1pab
integration year_dup, i(numid) j(year)
```

Run the traj plugin using a censored normal model, with "year_dup" as the independent variable and "sii" as the outcome of interest. The censored normal distribution ("cnorm") model is specified because the slope index of inequality is a repeatedly measured, continuous outcome censored by minimum and maximum values.

Run the plugin several times, changing only the number of groups specified ("order") and holding all other parameters constant. Select the model/group number that produces the highest BIC value.

```
traj, model(cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (0 0)
traj, model(cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (0 0 0)
traj, model(cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (0 0 0 0)
traj, model(cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (0 0 0 0 0)
```

The two- and three-group models produced large BIC and entropy values, so we will move forward with these options. Next, toggle the polynomial order for each of the three groups to achieve the largest possible BIC. The model below represents the tested option with a high BIC value, high entropy, and at least 1% membership in the smallest group.

```
traj, model (cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (1 1 0 0)
tcov(integration*) detail
```

Plot the trajectories for the three groups, along with accompanying confidence intervals. Assessing the confidence intervals provides an additional diagnostic check for the model (i.e., narrower, non-overlapping CIs are preferred).

```
trajplot, xtitle("Year") ytitle("Slope Index of Inequality") xlabel(2003(2)2019) ci
```

Perform parametric bootstrap sampling to estimate group size confidence intervals. Use parameter estimates from the traj output as the starting values for the matrix command.

```
matrix strt = 14.12135, -0.00700, 0.03105, 9.45529, -0.00460, -0.06057, 0.37896, -
0.01164, 0.71572, -0.52993, 0.09372, 39.33128, 30.01243, 26.53334, 4.12295

bootstrap _b (100/(1+exp(_b[theta2]))) (100*exp(_b[theta2])/(1+exp(_b[theta2]))),
reps(1000) dots(10): traj, model(cnorm) var(sii*) indep(year_dup*) min(-1000)
max(1000) order(1 1 0 0) tcov(integration*) start(strt) novar

estat bootstrap, percentile bc
```

Create a program, "trajstats," to calculate several other diagnostic criteria for group-based trajectory models.

```
program trajstats

preserve
```

This step calculates the average posterior probability.

```
generate Mp=0

foreach i of varlist _traj_ProbG* {
            replace Mp = `i' if `i' > Mp
        }
   sort _traj_Group

by _traj_Group: generate countG = _N
```

This step calculates the odds of correct classification.

```
   by _traj_Group: egen groupAPP = mean(Mp)
   by _traj_Group: generate counter = _n
   generate n = groupAPP/(1 - groupAPP)
   generate p = countG/ _N
   generate d = p/(1-p)
   generate occ = n/d
```

This step calculates the estimated group probabilities vs. the proportion of the sample assigned to the group.

```
        scalar c = 0
   gen TotProb = 0
   foreach i of varlist _traj_ProbG* {
     scalar c = c + 1
     quietly summarize `i'
     replace TotProb = r(sum)/ _N if _traj_Group == c
   }
        gen d_pp = TotProb/(1 - TotProb)
        gen occ_pp = n/d_pp
```

*This step displays:

*Group number [_traj_~p],

*Count per group (based on the max post prob), [countG]

*Average posterior probability for each group, [groupAPP]

*Odds of correct classification (based on the maximum posterior group assignment rule), [occ]

*Odds of correct classification (based on the weighted posterior probabilities), [occ_pp]

Observed probability of groups [p] versus the probability based on the posterior probabilities [TotProb]

```
list _traj_Group countG groupAPP occ occ_pp p TotProb if counter == 1

restore

end
```

Now, run the trajstats program.

```
trajstats
```

Create a list of group assignments and group membership probabilities for all subjects.

```
list _traj_Group - _traj_ProbG4
```

Reshape the dataset from wide to long format.

```
reshape long
```

```
*Perform multinomial logistic regression to identify covariates with statistically significant
associations with group membership, setting Group 1 membership as the base
outcome.*

drop if year < 2003

mlogit _traj_Group income2 region2 femeduc polstability goveffect corrupt gii oopexp
govexp exthlth land lingfrac distance integration, baseoutcome(1) rrr

******************************
***Close log and save as PDF***
******************************

log close

translate gbtmsoc.smcl gbtmsoc.pdf
```

APPENDIX H

Group-Based Trajectory Model
Socioeconomic Equity (Imputed)

```
*Install the traj package.*
net from https://www.andrew.cmu.edu/user/bjones/traj
net install traj
help traj

log using migbtmsoc

*Import dataset.*

import delimited "[redacted]Integrated Vaccine Delivery & Equity.csv"

*Assign labels to each variable in the dataset.*

label variable alpha3 "Alpha-3 Code"
label variable region "World Bank Region"
label variable income "Income Level"
label variable q5coverage "MCV1 Coverage in the Wealthiest Quintile"
label variable q4coverage "MCV1 Coverage in the 4th Quintile"
label variable q3coverage "MCV1 Coverage in the 3rd Quintile"
label variable q2coverage "MCV1 Coverage in the 2nd Quintile"
label variable q1coverage "MCV1 Coverage in the Poorest Quintile"
label variable geoequity "Geographic Equity"
label variable sii "Slope Index of Inequality"
label variable dtp3 "DTP3 Coverage"
label variable mcv1 "MCV1 Coverage"
label variable anc1 "Antenatal Care Coverage (1+ Visits)"
label variable pab "Protection at Birth Against Neonatal Tetanus"
label variable femeduc "Female Primary Education Completed"
label variable polstability "Political Stability"
label variable goveffect "Government Effectiveness"
label variable corrupt "Corruption"
label variable gii "Gender Inequality Index"
label variable oopexp "Out-of-Pocket Health Expenditures"
label variable govexp "Domestic Government Health Expenditures"
label variable exthlth "External Health Spending"
label variable land "Land Area"
label variable lingfrac "Linguistic Fractionalization"
```

```
label variable distance "Distance to Nearest Health Facility (Walking, 60+ Minutes)"

********************************************************
***Perform multiple imputation to handle missing data***
********************************************************

*First, identify missing values in the dataset. Install the "mdesc" package if needed.*

mdesc q5coverage q4coverage q3coverage q2coverage q1coverage geoequity sii dtp3
mcv1 anc1 pab femeduc polstability goveffect corrupt gii oopexp govexp exthlth land
lingfrac distance

*Create a pairwise correlation matrix to identify potential auxiliary variables.*

pwcorr q5coverage q4coverage q3coverage q2coverage q1coverage geoequity sii dtp3
mcv1 anc1 pab femeduc polstability goveffect corrupt gii oopexp govexp exthlth land
lingfrac distance

*Set the data for multiple imputation. The "mi set mlong" command generates three
additional variables that Stata will use to track the imputed datasets and values.*

mi set flong

*Summarize missing values in the dataset.*

mi misstable summarize q5coverage q4coverage q3coverage q2coverage q1coverage
geoequity sii dtp3 mcv1 anc1 pab femeduc polstability goveffect corrupt gii oopexp
govexp exthlth land lingfrac distance

*Summarize missing patterns in the dataset.*

mi misstable patterns q5coverage q4coverage q3coverage q2coverage q1coverage
geoequity sii dtp3 mcv1 anc1 pab femeduc polstability goveffect corrupt gii oopexp
govexp exthlth land lingfrac distance

*Register the variables to be imputed.*

mi register imputed q5coverage q4coverage q3coverage q2coverage q1coverage
geoequity sii anc1 pab

*Specify the imputed model.*

mi impute mvn geoequity anc1 pab = mcv1, add(10) rseed(54321) force
```

Specify a linear regression model to estimate the missing values. esample(imputed) creates a new variable, "imputed," that equals 1 for observations that are used in the imputation and 0 otherwise.

```
mi estimate, esample(imputed): regress q5coverage q4coverage q3coverage
q2coverage q1coverage sii geoequity anc1 pab
```

Create a table of observations not used in the imputation model.

```
tabulate country year if imputed == 0
```

Perform a diagnostic check to assess how well the imputation was performed; check inflation of standard errors.

```
mi estimate, vartable dftable

drop imputed
```

****

Creating new variables for integrated vaccine delivery + miscellaneous.

****

```
generate integration = 0
label variable integration "Integrated Vaccine Delivery"
```

Create new variables representing all possible absolute differences between MCV1, DTP3, ANC1, and PAB coverage levels.

```
generate abs_mcv1dtp3 = abs(mcv1-dtp3)
generate abs_mcv1anc1 = abs(mcv1-anc1)
generate abs_mcv1pab = abs(mcv1-pab)
generate abs_dtp3anc1 = abs(dtp3-anc1)
generate abs_dtp3pab = abs(dtp3-pab)
generate abs_anc1pab = abs(anc1-pab)
```

Set "integration" to 1 if coverage of all four services (MCV1, DTP3, ANC1, PAB) is greater than or equal to 70%, and all four are within 10 percentage points of one another.

```
replace integration = 1 if mcv1>=70 & dtp3>=70 & anc1>=70 & pab>=70 &
abs_mcv1dtp3<=10 & abs_mcv1anc1<=10 & abs_mcv1pab<=10 & abs_dtp3anc1<=10
& abs_dtp3pab<=10 & abs_anc1pab<=10
```

```
*Create a table summarizing events (i.e., "integration" = 1) by country."

tabulate country integration

*Create a new variable ("year_dup") that duplicates the "Year" column of the dataset.*

generate year_dup = year

*Encode alpha3, region, and income (string variables) as numeric variables "numid,"
"region2," and "income2."*

encode alpha3, generate(numid)
sort numid

encode region, generate(region2)

encode income, generate(income2)

*************************************************************
***Group-based trajectory analysis for socioeconomic equity***
*************************************************************

*Reshape the dataset from long to wide format; wide format is required to run the traj
Stata plugin.*

mi reshape wide country region region2 income income2 alpha3 q5coverage
q4coverage q3coverage q2coverage q1coverage geoequity sii dtp3 mcv1 anc1 pab
femeduc polstability goveffect corrupt gii oopexp govexp exthlth land lingfrac distance
abs_mcv1dtp3 abs_mcv1anc1 abs_mcv1pab abs_dtp3anc1 abs_dtp3pab abs_anc1pab
integration year_dup, i(numid) j(year)

*Run the traj plugin using a censored normal model, with "year_dup" as the
independent variable and "sii" as the outcome of interest. The censored normal
distribution ("cnorm") model is specified because the slope index of inequality is a
repeatedly measured, continuous outcome censored by minimum and maximum
values.*

*Run the plugin several times, changing only the number of groups specified ("order")
and holding all other parameters constant. Select the model/group number that
produces the highest BIC value.*

traj, model(cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (0 0)
```

```
traj, model(cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (0 0 0)
traj, model(cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (0 0 0 0)
traj, model(cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (0 0 0 0 0)

*The three-group model produced large BIC and entropy values, so we will move
forward with this option. Next, toggle the polynomial order for each of the three groups
to achieve the largest possible BIC. The model below represents the tested option with
a high BIC value, high entropy, and at least 1% membership in the smallest group.*

traj, model (cnorm) var(sii*) indep(year_dup*) min(-1) max(1) order (1 1)
tcov(integration*) detail

*Plot the trajectories for the three groups, along with accompanying confidence
intervals. Assessing the confidence intervals provides an additional diagnostic check for
the model (i.e., narrower, non-overlapping CIs are preferred).*

trajplot, xtitle("Year") ytitle("Slope Index of Inequality") xlabel(2003(2)2019) ci

*Perform parametric bootstrap sampling to estimate group size confidence intervals.
Use parameter estimates from the traj output as the starting values for the matrix
command.*

matrix strt = 8.93461, -0.00438, -0.05382, -4.47525, 0.00244, -0.11771, 0.12886,
68.85199, 31.14801

bootstrap _b (100/(1+exp(_b[theta2]))) (100*exp(_b[theta2])/(1+exp(_b[theta2]))),
reps(1000) dots(10): traj, model(cnorm) var(sii*) indep(year_dup*) min(-1000)
max(1000) order(1 1) tcov(integration*) start(strt) novar

estat bootstrap, percentile bc

*Create a program, "trajstats," to calculate several other diagnostic criteria for group-
based trajectory models.*

program trajstats

preserve

*This step calculates the average posterior probability.*

generate Mp=0

foreach i of varlist _traj_ProbG* {
```

```
            replace Mp = `i' if `i' > Mp
        }
    sort _traj_Group

by _traj_Group: generate countG = _N

*This step calculates the odds of correct classification.*

    by _traj_Group: egen groupAPP = mean(Mp)
    by _traj_Group: generate counter = _n
    generate n = groupAPP/(1 - groupAPP)
    generate p = countG/ _N
    generate d = p/(1-p)
    generate occ = n/d

*This step calculates the estimated group probabilities vs. the proportion of the sample
assigned to the group.*

        scalar c = 0
    gen TotProb = 0
    foreach i of varlist _traj_ProbG* {
      scalar c = c + 1
      quietly summarize `i'
      replace TotProb = r(sum)/ _N if _traj_Group == c
    }
        gen d_pp = TotProb/(1 - TotProb)
        gen occ_pp = n/d_pp

 *This step displays:
        *Group number [_traj_~p],
        *Count per group (based on the max post prob), [countG]
        *Average posterior probability for each group, [groupAPP]
        *Odds of correct classification (based on the maximum posterior group
        assignment rule), [occ]
        *Odds of correct classification (based on the weighted posterior probabilities),
        [occ_pp]
        *Observed probability of groups [p] versus the probability based on the posterior
        probabilities [TotProb]*

list _traj_Group countG groupAPP occ occ_pp p TotProb if counter == 1

restore
```

end

Now, run the trajstats program.

trajstats

Create a list of group assignments and group membership probabilities for all subjects.

list _traj_Group - _traj_ProbG2

Reshape the dataset from wide to long format.

mi reshape long country region region2 income income2 alpha3 q5coverage q4coverage q3coverage q2coverage q1coverage geoequity sii dtp3 mcv1 anc1 pab femeduc polstability goveffect corrupt gii oopexp govexp exthlth land lingfrac distance abs_mcv1dtp3 abs_mcv1anc1 abs_mcv1pab abs_dtp3anc1 abs_dtp3pab abs_anc1pab integration year_dup, i(numid) j(year)

drop if year < 2003

Perform multinomial logistic regression to identify covariates with statistically significant associations with group membership, setting Group 1 membership as the base outcome.

mlogit _traj_Group income2 region2 femeduc polstability goveffect corrupt gii oopexp govexp exthlth land lingfrac distance integration, baseoutcome(1) rrr

****
Close log and save as PDF
****

log close

translate migbtmsoc.smcl migbtmsoc.pdf

REFERENCES

1. Yeyati EL, Filippini F. *Social and Economic Impact of COVID-19*. Brookings Institute; 2021. https://www.brookings.edu/wp-content/uploads/2021/06/Social-and-economic-impact-COVID.pdf
2. Pike J, Melnick A, Gastañaduy PA, et al. Societal Costs of a Measles Outbreak. *Pediatrics*. 2021;147(4):e2020027037. doi:10.1542/peds.2020-027037
3. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations Department of Economic and Social Affairs Sustainable Development. Accessed February 18, 2022. https://sdgs.un.org/2030agenda
4. Universal Health Coverage. World Health Organization. Accessed February 18, 2022. https://www.who.int/westernpacific/health-topics/universal-health-coverage
5. Wondmeneh S. The last mile: endgame challenges in disease eradication. Institute for Public Health. Published February 27, 2017. Accessed February 18, 2022. https://publichealth.wustl.edu/last-mile-endgame-challenges-disease-eradication/
6. Klepac P, Funk S, Hollingsworth TD, Metcalf CJE, Hampson K. Six challenges in the eradication of infectious diseases. *Epidemics*. 2015;10:97-101. doi:10.1016/j.epidem.2014.12.001
7. Vilas VJDR, de Carvalho MJF de, Vigilato MAN, et al. Tribulations of the Last Mile: Sides from a Regional Program. *Front Vet Sci*. 2017;4. doi:10.3389/fvets.2017.00004
8. Klepac P, Metcalf CJE, McLean AR, Hampson K. Towards the endgame and beyond: complexities and challenges for the elimination of infectious diseases. *Philos Trans R Soc B Biol Sci*. 2013;368(20120137). doi:http://dx.doi.org/10.1098/rstb.2012.0137
9. Masresha BG, Luce, Jr. R, Weldegebriel G, Katsande R, Gasasira A, Mihigo R. The impact of a prolonged ebola outbreak on measles elimination activities in Guinea, Liberia and Sierra Leone, 2014-2015. *Pan Afr Med J*. 2020;35(Suppl 1). doi:https://dx-doi-org.proxy1.library.jhu.edu/10.11604%2Fpamj.supp.2020.35.1.19059
10. Ogundele OA, Omotoso AA, Fagbemi AT. COVID-19 outbreak: a potential threat to routine vaccination programme activities in Nigeria. *Hum Vaccines Immunother*. 17(3):661-663. doi:https://doi-org.proxy1.library.jhu.edu/10.1080/21645515.2020.1815490
11. Sun X, Samba TT, Yao J, et al. Impact of the Ebola outbreak on routine immunization in western area, Sierra Leone - a field survey from an Ebola epidemic area. *BMC Public Health*. 2017;17(1):363. doi:10.1186/s12889-017-4242-7
12. At least 80 million children under one at risk of diseases such as diphtheria, measles and polio as COVID-19 disrupts routine vaccination efforts, warn Gavi, WHO and UNICEF. World Health Organization. Published May 22, 2020. Accessed February 18, 2022. https://www.who.int/news/item/22-05-2020-at-least-80-million-children-under-one-at-risk-of-diseases-such-as-diphtheria-measles-and-polio-as-covid-19-disrupts-routine-vaccination-efforts-warn-gavi-who-and-unicef

13. Oliveira-Cruz V, Kurowski C, Mills A. Delivery of priority health services: searching for synergies within the vertical versus horizontal debate. *J Int Dev*. 2003;15(1):67-86. doi:https://doi.org/10.1002/jid.966
14. Msuya J. *Horizontal and Vertical Delivery of Health Services: What Are The Trade Offs?* World Bank; 2003. https://documents1.worldbank.org/curated/en/914491468761944686/310436360_200502761000211/additional/269420Msuya1WDR1Background1paper.pdf
15. Anya BPM, Moturi E, Aschalew T, et al. Contribution of polio eradication initiative to strengthening routine immunization: Lessons learnt in the WHO African region. *Vaccine*. 2016;34(43):5187-5192. doi:10.1016/j.vaccine.2016.05.062
16. Chakrabarti A, Grépin KA, Helleringer S. The impact of supplementary immunization activities on routine vaccination coverage: An instrumental variable analysis in five low-income countries. *PLoS ONE*. 2019;14(2). doi:10.1371/journal.pone.0212049
17. World Health Organization. *Global Routine Immunization Strategies and Practices (GRISP): A Companion Document to the Global Vaccine Action Plan (GVAP)*. World Health Organization; 2016. Accessed February 26, 2022. https://apps.who.int/iris/handle/10665/204500
18. World Health Organization. *Global Vaccine Action Plan 2011–2020*. World Health Organization; 2013. https://apps.who.int/iris/rest/bitstreams/110564/retrieve
19. Deogaonkar R, Hutubessy R, van der Putten I, Evers S, Jit M. Systematic review of studies evaluating the broader economic impact of vaccination in low and middle income countries. *BMC Public Health*. 2012;12(1):878. doi:10.1186/1471-2458-12-878
20. Gupta M, Angeli F, Bosma H, et al. Effectiveness of Multiple-Strategy Community Intervention in Reducing Geographical, Socioeconomic and Gender Based Inequalities in Maternal and Child Health Outcomes in Haryana, India. *PLoS ONE*. 2016;11(3):e0150537. doi:https://doi.org/10.1371/journal.pone.0150537
21. Goodson JL, Kulkarni MA, Vanden Eng JL, et al. Improved equity in measles vaccination from integrating insecticide-treated bednets in a vaccination campaign, Madagascar. *Trop Med Int Health TM IH*. 2012;17(4):430-437. doi:10.1111/j.1365-3156.2011.02953.x
22. World Health Organization. *Pandemic Influenza Risk Management: WHO Interim Guidance*. World Health Organization; 2013. https://www.who.int/influenza/preparedness/pandemic/GIP_PandemicInfluenzaRiskManagementInterimGuidance_Jun2013.pdf
23. Long KM, McDermott F, Meadows GN. Being pragmatic about healthcare complexity: our experiences applying complexity theory and pragmatism to health services research. *BMC Med*. 2018;16(1):94. doi:10.1186/s12916-018-1087-6
24. Migiro S, Magangi BA. Mixed methods: A review of literature and the future of the new research paradigm. Published online 2011. doi:10.5897/AJBM09.082
25. Onwuegbuzie AJ, Leech NL. On Becoming a Pragmatic Researcher: The Importance of Combining Quantitative and Qualitative Research Methodologies. *Int J Soc Res Methodol*. 2005;8(5):375-387. doi:10.1080/13645570500402447

26. Ogilvie D, Bauman A, Foley L, Guell C, Humphreys D, Panter J. Making sense of the evidence in population health intervention research: building a dry stone wall | BMJ Global Health. *BMJ Glob Health*. 2020;5(e004017). Accessed February 18, 2022. https://gh.bmj.com/content/5/12/e004017
27. Dowdle WR. The principles of disease elimination and eradication. *Bull World Health Organ*. 1998;76(Suppl 2):22.
28. Craig R. The 'last mile' in education and training. TechCrunch. Published June 25, 2017. Accessed February 19, 2022. https://techcrunch.com/2017/06/25/the-last-mile-in-education-and-training/
29. Balcik B, Beamon BM, Smilowitz K. Last mile distribution in humanitarian relief. *J Intell Transp Syst*. 2008;12(2):51-63. doi:10.1080/15472450802023329
30. Macioszek E. First and Last Mile Delivery – Problems and Issues. In: Sierpiński G, ed. *Advanced Solutions of Transport Systems for Growing Mobility*. Advances in Intelligent Systems and Computing. Springer International Publishing; 2018:147-154. doi:10.1007/978-3-319-62316-0_12
31. Zipursky S, Djingarey MH, Lodjo JC, Olodo L, Tiendrebeogo S, Ronveaux O. Benefits of using vaccines out of the cold chain: delivering meningitis A vaccine in a controlled temperature chain during the mass immunization campaign in Benin. *Vaccine*. 2014;32(13):1431-1435. doi:10.1016/j.vaccine.2014.01.038
32. Chandani Y, Noel M, Pomeroy A, Andersson S, Pahl MK, Williams T. Factors affecting availability of essential medicines among community health workers in Ethiopia, Malawi, and Rwanda: solving the last mile puzzle. *Am J Trop Med Hyg*. 2012;87(5 Suppl):120-126. doi:10.4269/ajtmh.2012.11-0781
33. World Health Organization. Outbreak Investigation and Response. Published online 2009. Accessed February 19, 2022. https://www.who.int/diseasecontrol_emergencies/publications/idhe_2009_london_outbreaks.pdf
34. Doshi P. The elusive definition of pandemic influenza. *Bull World Health Organ*. 2011;89(7):532-538. doi:10.2471/BLT.11.086173
35. Stern J, Wu KJ. Endemicity Is Meaningless. The Atlantic. Published February 1, 2022. Accessed February 19, 2022. https://www.theatlantic.com/health/archive/2022/02/endemicity-means-nothing/621423/
36. UK Health Security Agency. Measles in England. UK Health Security Agency. Published August 19, 2019. Accessed February 19, 2022. https://ukhsa.blog.gov.uk/2019/08/19/measles-in-england/
37. Mowbray F, Marcu A, Godinho CA, Michie S, Yardley L. Communicating to increase public uptake of pandemic flu vaccination in the UK: Which messages work? *Vaccine*. 2016;34(28):3268-3274. doi:10.1016/j.vaccine.2016.05.006
38. Maurer J, Uscher-Pines L, Harris KM. Perceived seriousness of seasonal and A(H1N1) influenzas, attitudes toward vaccination, and vaccine uptake among U.S. adults: does the source of information matter? *Prev Med*. 2010;51(2):185-187. doi:10.1016/j.ypmed.2010.05.008

39. Razum O, Sridhar D, Jahn A, Zaidi S, Ooms G, Müller O. Polio: from eradication to systematic, sustained control. *BMJ Glob Health*. 2019;4(e001633). Accessed February 19, 2022. https://gh.bmj.com/content/4/4/e001633
40. Lee TH, Chen AH. Last-Mile Logistics of Covid Vaccination — The Role of Health Care Organizations. *N Engl J Med*. 2021;384:685-687. doi:10.1056/NEJMp2100574
41. Painter EM. Demographic Characteristics of Persons Vaccinated During the First Month of the COVID-19 Vaccination Program — United States, December 14, 2020–January 14, 2021. *MMWR Morb Mortal Wkly Rep*. 2021;70. doi:10.15585/mmwr.mm7005e1
42. Aryeetey E, Engebretsen E, Gornitzka Å, Maassen P, Stølen S. A step backwards in the fight against global vaccine inequities. *The Lancet*. 2021;397(10268):23-24. doi:10.1016/S0140-6736(20)32596-4
43. Saint-Victor DS, Omer SB. Vaccine refusal and the endgame: walking the last mile first. *Philos Trans R Soc Lond B Biol Sci*. 2013;368(1623):20120148. doi:10.1098/rstb.2012.0148
44. Onwuegbuzie AJ, Frels RK, Hwang E. Mapping Saldana's Coding Methods onto the Literature Review Process. *J Educ Issues*. 2016;2(1):130-150.
45. Saldaña J. Coding and Analysis Strategies. In: *The Oxford Handbook of Qualitative Research*. 1st ed. Oxford University Press; 2014. doi:10.1093/oxfordhb/9780199811755.013.001
46. Earp JA, Ennett ST. Conceptual models for health education research and practice. *Health Educ Res*. 1991;6(2):163-171. doi:10.1093/her/6.2.163
47. Ozawa S, Yemeke TT, Evans DR, Pallas SE, Wallace AS, Lee BY. Defining hard-to-reach populations for vaccination. *Vaccine*. 2019;37(37):5525-5534. doi:10.1016/j.vaccine.2019.06.081
48. Belda K, Tegegne AA, Mersha AM, Bayenessagne MG, Hussein I, Bezabeh B. Measles outbreak investigation in Guji zone of Oromia Region, Ethiopia. *Pan Afr Med J*. 2017;27(Suppl 2):9. doi:10.11604/pamj.supp.2017.27.2.10705
49. Kew O, Pallansch M. Breaking the Last Chains of Poliovirus Transmission: Progress and Challenges in Global Polio Eradication. *Annu Rev Virol*. 2018;5(1):427-451. doi:10.1146/annurev-virology-101416-041749
50. Bandyopadhyay AS, Macklin GR. Final frontiers of the polio eradication endgame. *Curr Opin Infect Dis*. 2020;33(5):404-410. doi:10.1097/QCO.0000000000000667
51. World Health Organization. Poliomyelitis (polio). World Health Organization. Accessed February 26, 2022. https://www.who.int/westernpacific/health-topics/poliomyelitis
52. Government of Pakistan. *National Emergency Action Plan for Polio Eradication, 2017-2018*. National Emergency Operations Centre; 2017. Accessed February 19, 2022. https://polioeradication.org/wp-content/uploads/2016/07/NEAP-2017_2018_v6.pdf
53. Simpson DM, Sadr-Azodi N, Mashal T, et al. Polio eradication initiative in Afghanistan, 1997-2013. *J Infect Dis*. 2014;210 Suppl 1:S162-172. doi:10.1093/infdis/jiu022

54. Global Polio Eradication Initiative. Polio Now. Global Polio Eradication Initiative. Accessed February 26, 2022. https://polioeradication.org/polio-today/polio-now/
55. History of Smallpox. Centers for Disease Control & Prevention. Published February 21, 2021. Accessed February 19, 2022. https://www.cdc.gov/smallpox/history/history.html
56. de Lataillade C, Auvergne S, Delannoy I. 2005 and 2006 seasonal influenza vaccination coverage rates in 10 countries in Africa, Asia Pacific, Europe, Latin America and the Middle East. *J Public Health Policy*. 2009;30(1):83-101. doi:10.1057/jphp.2008.40
57. Esteghamati A, Gouya MM, Zahraei SM, Dadras MN, Rashidi A, Mahoney F. Progress in measles and rubella elimination in Iran. *Pediatr Infect J*. 2007;26(12):1137-1141.
58. Farag NH, Alexander J, Hadler S, et al. Progress toward poliomyelitis eradication -- Afghanistan and Pakistan, January 2013-August 2014. *MMWR Morb Mortal Wkly Rep*. 2014;63(43):973-977.
59. Griffiths UK, Mounier-Jack S, Oliveira-Cruz V, Balabanova D, Hanvoravongchai P, Ongolo P. How can measles eradication strengthen health care systems? *J Infect Dis*. 2011;204 Suppl 1:S78-81. doi:10.1093/infdis/jir090
60. Warigon C, Mkanda P, Muhammed A, et al. Demand Creation for Polio Vaccine in Persistently Poor-Performing Communities of Northern Nigeria: 2013-2014. *J Infect Dis*. 2016;213 Suppl 3:S79-85. doi:10.1093/infdis/jiv511
61. Jawaid A. Vigilance, Cooperation Needed to Beat Resurgent Polio. IPI Global Observatory. Published October 24, 2016. Accessed February 19, 2022. https://theglobalobservatory.org/2016/10/cooperation-needed-to-beat-resurgent-polio/
62. Grassly NC. The final stages of the global eradication of poliomyelitis. *Philos Trans R Soc Lond B Biol Sci*. 2013;368(1623):20120140. doi:10.1098/rstb.2012.0140
63. Yusufzai A. Challenges of Polio Vaccination. Inter Press Agency. Published March 29, 2016. Accessed February 19, 2022. http://www.ipsnews.net/2016/03/challenges-of-polio-vaccination/
64. Ganapathiraju PV, Morssink CB, Plumb J. Endgame for polio eradication? Options for overcoming social and political factors in the progress to eradicating polio. *Glob Public Health*. 2015;10(4):463-473. doi:10.1080/17441692.2014.994655
65. Ferrinho P, Dramé M, Biai S, Lopes O, Sousa F de, Van Lerberghe W. Perceptions of the usefulness of external support to immunization coverage in Guinea-Bissau: a Delphi analysis of the GAVI-Alliance cash-based support. *Rev Soc Bras Med Trop*. 2013;46(1):7-14. doi:10.1590/0037-868216612013
66. von Seidlein L, Jiddawi M, Grais RF, Luquero F, Lucas M, Deen J. Value of and Challenges for Cholera Vaccines in Africa. *J Infect Dis*. 2013;208(Suppl 1):S8-S14.
67. Fields R, Dabbagh A, Jain M, Sagar KS. Moving forward with strengthening routine immunization delivery as part of measles and rubella elimination activities. *Vaccine*. 2013;31 Suppl 2:B115-121. doi:10.1016/j.vaccine.2012.11.094

68. Orenstein WA, Hinman A, Nkowane B, Olive JM, Reingold A. Measles and Rubella Global Strategic Plan 2012-2020 midterm review. *Vaccine*. 2018;36 Suppl 1:A1-A34. doi:10.1016/j.vaccine.2017.09.026
69. Taylor S. Political epidemiology: strengthening socio-political analysis for mass immunisation - lessons from the smallpox and polio programmes. *Glob Public Health*. 2009;4(6):546-560. doi:10.1080/17441690701727850
70. Yehualashet YG, Horton J, Mkanda P, et al. Intensified Local Resource Mobilization for the Polio Eradication Initiative: The Experience of World Health Organization in Nigeria During 2008–2015. *J Infect Dis*. 2016;213(Suppl 3):S101. doi:10.1093/infdis/jiv535
71. Rockers PC, Kruk ME, Laugesen MJ. Perceptions of the Health System and Public Trust in Government in Low and Middle-Income Countries: Evidence from the World Health Surveys | Journal of Health Politics, Policy and Law | Duke University Press. *J Health Polit Policy Law*. 2012;37(3):405-437.
72. Ozawa S, Paina L, Qiu M. Exploring pathways for building trust in vaccination and strengthening health system resilience. *BMC Health Serv Res*. 2016;16(7):639. doi:10.1186/s12913-016-1867-7
73. Mullaney A, Hassan SA. He Led the CIA to bin Laden—and Unwittingly Fueled a Vaccine Backlash. National Geographic. Published February 27, 2015. Accessed February 19, 2022. https://www.nationalgeographic.com/science/article/150227-polio-pakistan-vaccination-taliban-osama-bin-laden
74. Global Polio Eradication Initiative. Annual Report 2009. Published online 2009. Accessed February 19, 2022. https://polioeradication.org/wp-content/uploads/2016/07/AnnualReport2009_ENG.pdf
75. World Health Organization. Statement of the Twenty-first IHR Emergency Committee Regarding the International Spread of Poliovirus. World Health Organization. Published May 29, 2019. Accessed February 26, 2022. https://www.who.int/news/item/29-05-2019-statement-of-the-twenty-first-ihr-emergency-committee
76. Polio Eradication Committee, Indian Academy of Pediatrics, Vashishtha VM, et al. Recommendations of 2nd National Consultative Meeting of Indian Academy of Pediatrics (IAP) on polio eradication and improvement of routine immunization. *Indian Pediatr*. 2008;45(5):367-378.
77. Gebre T. Rethinking disease eradication: putting countries first. *Int Health*. 2021;13(3):215-221. doi:10.1093/inthealth/ihab011
78. Chaignat CL, Monti V, Soepardi J, et al. Cholera in disasters: do vaccines prompt new hopes? *Expert Rev Vaccines*. 2008;7(4):431-435. doi:10.1586/14760584.7.4.431
79. Zurn P, Dal Poz MR, Stilwell B, Adams O. Imbalance in the health workforce. *Hum Resour Health*. 2004;2(1):13. doi:10.1186/1478-4491-2-13
80. Global Polio Eradication Initiative. Guidelines for Implementing Polio Surveillance in Hard-to-Reach Areas & Populations. Published online 2018. https://polioeradication.org/wp-content/uploads/2020/10/Guidelines-polio-surveillance-H2R-areas.pdf

81. Global Polio Eradication Initiative. Technical Brief: Gender. Published online 2018. Accessed February 19, 2022. https://polioeradication.org/wp-content/uploads/2018/03/polio-vacciation-GPEI-gender-technical-brief-summary_2018-20180816update.pdf
82. Global Polio Eradication Initiative. Polio Endgame Strategy 2019-2023: Eradication, Integration, Certification, and Containment. Published online 2019. Accessed February 22, 2022. https://polioeradication.org/wp-content/uploads/2019/06/english-polio-endgame-strategy.pdf
83. Obradovic Z, Balta S, Obradovic A, Mesic S. The Impact of War on Vaccine Preventable Diseases. *Mater Socio-Medica*. 2014;26(6):382. doi:10.5455/msm.2014.26.382-384
84. Bhutta ZA. The last mile in global poliomyelitis eradication. *Lancet Lond Engl*. 2011;378(9791):549-552. doi:10.1016/S0140-6736(11)60744-7
85. Biellik RJ, Orenstein WA. Strengthening routine immunization through measles-rubella elimination. *Vaccine*. 2018;36(37):5645-5650. doi:10.1016/j.vaccine.2018.07.029
86. Peters DH, Paina L, Bennett S. Expecting the unexpected: applying the Develop-Distort Dilemma to maximize positive market impacts in health. *Health Policy Plan*. 2012;27(suppl_4):iv44-iv53. doi:10.1093/heapol/czs085
87. Hitchins R, Elliott D, Gibson A. Making business service markets work for the poor in rural areas: a review of experience. Published online June 2004. http://www.bdsknowledge.org/dyn/bds/docs/329/Business%20services%20in%20weaker%20mkts_DFID.pdf
88. Andrus JK, Cochi SL, Cooper LZ, Klein JD. Combining Global Elimination Of Measles And Rubella With Strengthening Of Health Systems In Developing Countries. *Health Aff Proj Hope*. 2016;35(2):327-333. doi:10.1377/hlthaff.2015.1005
89. Mantel C, Chu SY, Hyde TB, Lambach P, IPIE Pilot Implementation Group. Seasonal influenza vaccination in middle-income countries: Assessment of immunization practices in Belarus, Morocco, and Thailand. *Vaccine*. 2020;38(2):212-219. doi:10.1016/j.vaccine.2019.10.028
90. Wagner AL. The use and significance of vaccination cards. *Hum Vaccin Immunother*. 2019;15(12):2844-2846. doi:10.1080/21645515.2019.1625647
91. Grabenstein JD, Nevin RL. Mass immunization programs: principles and standards. *Curr Top Microbiol Immunol*. 2006;304:31-51. doi:10.1007/3-540-36583-4_3
92. Ozisik L, Tanriover MD, Altınel S, Unal S. Vaccinating healthcare workers: Level of implementation, barriers and proposal for evidence-based policies in Turkey. *Hum Vaccines Immunother*. 2017;13(5):1198-1206. doi:10.1080/21645515.2016.1269992
93. Dasgupta R, Chaturvedi S, Adhish SV, et al. Social determinants and polio “endgame”: a qualitative study in high risk districts of India. *Indian Pediatr*. 2008;45(5):357-365.
94. IOM Pakistan. Assessment of Incoming Afghan Nationals (Torkham Border). Published online June 2017. https://www.iom.int/sites/default/files/situation_reports/file/IOMPakistan_0617_AssessmentofIncomingAfghanNationals%28Torkham%20Border%29.pdf

95. National Emergency Operations Centre. National Emergency Action Plan for Polio Eradication, 2016-2017. Accessed February 22, 2022. https://polioeradication.org/wp-content/uploads/2016/11/NEAP2016-2017_Pakistan.pdf
96. Yusufzai A. Pakistan, Afghanistan need extra efforts to eradicate polio. ReliefWeb. Published January 13, 2016. Accessed February 19, 2022. https://reliefweb.int/report/pakistan/pakistan-afghanistan-need-extra-efforts-eradicate-polio
97. Uzoma I, Adewara K, Bashir B, et al. Nomadic Route Identification and Polio Vaccination Activities for Unreached Mobile Population in Barno State, Northeast Nigeria | IEEE Conference Publication | IEEE Xplore. In: ; 2019:1-4. doi:https://doi.org/10.1109/GHTC46095.2019.9033109
98. Lopalco PL. Wild and vaccine-derived poliovirus circulation, and implications for polio eradication. *Epidemiol Infect*. 2017;145(3):413-419. doi:10.1017/S0950268816002569
99. U.S. Centers for Disease Control & Prevention. Ring Vaccination. Published November 29, 2019. Accessed February 19, 2022. https://www.cdc.gov/smallpox/bioterrorism-response-planning/public-health/ring-vaccination.html
100. Gumede N, Okeibunor J, Diop O, et al. Progress on the Implementation of Environmental Surveillance in the African Region, 2011-2016. *J Immunol Sci*. 2018;Suppl(4):24-30.
101. Susanti N, Herna, Puspandari N, Purnamawati S. Progress and Challenges of Polio Environmental Surveillance in Indonesia. In: Atlantis Press; 2020:202-205. doi:10.2991/ahsr.k.200215.038
102. Hamisu AW, Johnson TM, Craig K, et al. Strategies for Improving Polio Surveillance Performance in the Security-Challenged Nigerian States of Adamawa, Borno, and Yobe During 2009-2014. *J Infect Dis*. 2016;213 Suppl 3:S136-139. doi:10.1093/infdis/jiv530
103. Haydon DT, Cleaveland S, Taylor LH, Laurenson MK. Identifying reservoirs of infection: a conceptual and practical challenge. *Emerg Infect Dis*. 2002;8(12):1468-1473. doi:10.3201/eid0812.010317
104. Warmbrod KL, West R, Frieman M, George D, Martin E, Rivers C. *Staying Ahead of the Variants: Policy Recommendations to Identify and Manage Current and Future Variants of Concern*. The Johns Hopkins Center for Health Security Accessed February 19, 2022. https://www.centerforhealthsecurity.org/our-work/pubs_archive/pubs-pdfs/2021/20210216-covid19-variants.pdf
105. U.S. Centers for Disease Control & Prevention. Variants and Genomic Surveillance for SARS-CoV-2. Centers for Disease Control and Prevention. Published February 11, 2020. Accessed February 26, 2022. https://www.cdc.gov/coronavirus/2019-ncov/variants/variant-surveillance.html
106. Durlak JA. Why Program Implementation is Important: Journal of Prevention & Intervention in the Community: Vol 17, No 2. *J Prev Interv Community*. 2008;17(2):5-18.

107. MacDonald M, Pauly B, Wong G, et al. Supporting successful implementation of public health interventions: protocol for a realist synthesis. *Syst Rev*. 2016;5. doi:10.1186/s13643-016-0229-1
108. Ivers LC, Farmer PE, Pape WJ. Oral cholera vaccine and integrated cholera control in Haiti. *Lancet Lond Engl*. 2012;379(9831):2026-2028. doi:10.1016/S0140-6736(12)60832-0
109. Blecher MS, Hussey G, Keen GA, Eggers R, Girdler-Brown B. Eradication of poliomyelitis in South Africa. *South Afr Med J Suid-Afr Tydskr Vir Geneeskd*. 1994;84(10):664-668.
110. Tevi-Benissan C, Okeibunor J, Châtellier GM du, et al. Introduction of Inactivated Poliovirus Vaccine and Trivalent Oral Polio Vaccine/Bivalent Oral Polio Vaccine Switch in the African Region. *J Infect Dis*. 2017;216(Suppl 1):S66. doi:10.1093/infdis/jiw616
111. World Health Organization. Statement of the Seventeenth IHR Emergency Committee Regarding the International Spread of Poliovirus. World Health Organization. Published May 10, 2018. Accessed February 19, 2022. https://www.who.int/news/item/10-05-2018-statement-of-the-seventeenth-ihr-emergency-committee-regarding-the-international-spread-of-poliovirus
112. World Health Organization. Statement of the Twenty-Third IHR Emergency Committee Regarding the International Spread of Poliovirus. World Health Organization. Published January 7, 2020. Accessed February 19, 2022. https://www.who.int/news/item/07-01-2020-statement-o-the-twenty-third-ihr-emergency-committee-regarding-the-international-spread-of-poliovirus
113. Vitek CR, Wharton M. Diphtheria in the former Soviet Union: reemergence of a pandemic disease. *Emerg Infect Dis*. 1998;4(4):539.
114. National Emergency Operations Centre. Pakistan: National Emergency Action Plan for Polio Eradication 2018/2019. Published online June 2019. Accessed February 19, 2022. https://reliefweb.int/sites/reliefweb.int/files/resources/Pakistan%20National%20Emergency%20Action%20Plan%20for%20Polio%20Eradication%2020182019%20%281st%20July%202018%20-%2030th%20June%202019%29.pdf
115. Deal A, Hayward SE, Huda M, et al. Strategies and action points to ensure equitable uptake of COVID-19 vaccinations: A national qualitative interview study to explore the views of undocumented migrants, asylum seekers, and refugees. Published online April 19, 2021:2021.04.12.21255313. doi:10.1101/2021.04.12.21255313
116. Harries J, Moodley J, Barone MA, Mall S, Sinanovic E. Preparing for HPV vaccination in South Africa: key challenges and opinions. *Vaccine*. 2009;27(1):38-44. doi:10.1016/j.vaccine.2008.10.033
117. Omer SB, Salmon DA, Orenstein WA, deHart MP, Halsey N. Vaccine refusal, mandatory immunization, and the risks of vaccine-preventable diseases. *N Engl J Med*. 2009;360(19):1981-1988. doi:10.1056/NEJMsa0806477
118. Payaprom Y, Bennett P, Burnard P, Alabaster E, Tantipong H. Understandings of influenza and influenza vaccination among high-risk urban dwelling Thai adults: a

qualitative study. *J Public Health Oxf Engl*. 2010;32(1):26-31. doi:10.1093/pubmed/fdp086
119. Wu S, Yang P, Li H, Ma C, Zhang Y, Wang Q. Influenza vaccination coverage rates among adults before and after the 2009 influenza pandemic and the reasons for non-vaccination in Beijing, China: a cross-sectional study. *BMC Public Health*. 2013;13:636. doi:10.1186/1471-2458-13-636
120. Cunha SC, Dourado I. MMR mass vaccination campaigns, vaccine-related adverse events, and the limits of the decision making process, in Brazil. *Health Policy Amst Neth*. 2004;67(3):323-328. doi:10.1016/j.healthpol.2003.07.008
121. Cousins S. Syrian crisis: health experts say more can be done. *The Lancet*. 385(9972):931-934. doi:doi: 10.1016/S0140-6736(15)60515-3
122. Gul A. Pakistan Arrests Parents for Refusing Polio Drops. VOA. Published March 2, 2015. Accessed February 19, 2022. https://www.voanews.com/a/pakistan-arrests-parents-for-refusing-polio-drops/2664959.html
123. Metselaar D, McDonald K, Gemert W, van Rens MM, Muller AS. Poliomyelitis: epidemiology and prophylaxis - PMC. *Bull World Health Organ*. 1977;55(6):755-759.
124. Schoberg D. Why the last mile is so important. End Polio. Published March 19, 2019. Accessed February 19, 2022. https://www.endpolio.org/why-the-last-mile-is-so-important
125. Kew OM, Sutter RW, de Gourville EM, Dowdle WR, Pallansch MA. Vaccine-derived polioviruses and the endgame strategy for global polio eradication. *Annu Rev Microbiol*. 2005;59:587-635. doi:10.1146/annurev.micro.58.030603.123625
126. Lloyd-Smith JO. Vacated niches, competitive release and the community ecology of pathogen eradication. *Philos Trans R Soc B Biol Sci*. 2013;368(1623). doi:10.1098/rstb.2012.0150
127. Kennedy DA, Read AF. Why does drug resistance readily evolve but vaccine resistance does not? *Proc Biol Sci*. 2017;284(1851):20162562. doi:10.1098/rspb.2016.2562
128. Maiden MCJ. The impact of protein-conjugate polysaccharide vaccines: an endgame for meningitis? *Philos Trans R Soc Lond B Biol Sci*. 2013;368(1623):20120147. doi:10.1098/rstb.2012.0147
129. Thompson KM, Duintjer Tebbens RJ. National choices related to inactivated poliovirus vaccine, innovation and the endgame of global polio eradication. *Expert Rev Vaccines*. 2014;13(2):221-234. doi:10.1586/14760584.2014.864563
130. Willyard C. Polio: The eradication endgame. *Nature*. 2014;507(7490):S14-15. doi:10.1038/507s14a
131. Nathanson N, Kew OM. From emergence to eradication: the epidemiology of poliomyelitis deconstructed. *Am J Epidemiol*. 2010;172(11):1213-1229. doi:10.1093/aje/kwq320
132. Francis T. On the Doctrine of Original Antigenic Sin. *Proc Am Philos Soc*. 1960;104(6):572-578.

133. Monto AS, Malosh RE, Petrie JG, Martin ET. The Doctrine of Original Antigenic Sin: Separating Good From Evil. *J Infect Dis*. 2017;215(12):1782-1788. doi:10.1093/infdis/jix173
134. Estívariz CF, Pallansch MA, Anand A, et al. Poliovirus vaccination options for achieving eradication and securing the endgame. *Curr Opin Virol*. 2013;3(3):309-315. doi:10.1016/j.coviro.2013.05.007
135. Wolff J, Atuire C, Bhan A, et al. Ethical and policy considerations for COVID-19 vaccination modalities: delayed second dose, fractional dose, mixed vaccines. *BMJ Glob Health*. 2021;6(5):e005912. doi:10.1136/bmjgh-2021-005912
136. Nareth L, Aylward RB, Sopal O, Bassett D, Vun MC, Bilous J. Establishing acute flaccid paralysis surveillance under difficult circumstances: lessons learned in Cambodia. *J Infect Dis*. 1997;175 Suppl 1:S173-175. doi:10.1093/infdis/175.supplement_1.s173
137. Orenstein WA, Committee on Infectious Diseases. Eradicating polio: how the world's pediatricians can help stop this crippling illness forever. *Pediatrics*. 2015;135(1):196-202. doi:10.1542/peds.2014-3163
138. Rao R. Why the vaccination supply chain needs reform. World Economic Forum. Accessed February 19, 2022. https://www.weforum.org/agenda/2016/05/why-the-vaccination-supply-chain-needs-reform/
139. Tebbens RJD, Thompson KM. Polio endgame risks and the possibility of restarting the use of oral poliovirus vaccine. *Expert Rev Vaccines*. 2018;17(8):739. doi:10.1080/14760584.2018.1506333
140. Wolfson LJ, Gasse F, Lee-Martin SP, et al. Estimating the costs of achieving the WHO-UNICEF Global Immunization Vision and Strategy, 2006-2015. *Bull World Health Organ*. 2008;86:27-39. doi:10.1590/S0042-96862008000100012
141. Barrett S. Economic considerations for the eradication endgame. *Philos Trans R Soc Lond B Biol Sci*. 2013;368(1623):20120149. doi:10.1098/rstb.2012.0149
142. World Health Organization. Global leaders pledge US$2.6 billion to eradicate polio at the Reaching the Last Mile Forum in Abu Dhabi. World Health Organization. Published November 19, 2019. Accessed February 19, 2022. https://www.who.int/news/item/19-11-2019-global-leaders-pledge-us-2.6-billion-to-eradicate-polio-at-the-reaching-the-last-mile-forum-in-abu-dhabi
143. World Health Organization. Twelfth meeting of the Emergency Committee under the International Health Regulations (2015) regarding the international spread of poliovirus. World Health Organization. Published February 13, 2017. Accessed February 19, 2022. https://www.who.int/news/item/13-02-2017-twelfth-meeting-of-the-emergency-committee-under-the-international-health-regulations-(2015)-regarding-the-international-spread-of-poliovirus
144. World Health Organization. WHO supports Angola's Government efforts to end polio outbreak. World Health Organization. Published December 2, 2019. Accessed February 19, 2022. https://www.afro.who.int/news/who-supports-angolas-government-efforts-end-polio-outbreak

145. World Health Organization. Statement on the 8th IHR Emergency Committee meeting regarding the international spread of poliovirus. World Health Organization. Published March 1, 2016. Accessed February 19, 2022. https://www.who.int/news/item/01-03-2016-statement-on-the-8th-ihr-emergency-committee-meeting-regarding-the-international-spread-of-poliovirus
146. Roberts L. Polio: The final assault? *Science*. 2004;303(5666):1960-1968. doi:10.1126/science.303.5666.1960
147. Government of Pakistan. National Emergency Action Plan for Polio Eradication, 2015-2016. Published online June 2015. Accessed February 19, 2022. https://reliefweb.int/sites/reliefweb.int/files/resources/Final-pakistan-NEAP2015-16.pdf
148. Hacisuleyman E, Hale C, Saito Y, et al. Vaccine Breakthrough Infections with SARS-CoV-2 Variants. *N Engl J Med*. 2021;384(23):2212-2218. doi:10.1056/NEJMoa2105000
149. Goldhill O. "We're being left behind": Rural hospitals can't afford ultra-cold freezers to store the leading Covid-19 vaccine. *STAT*. https://www.statnews.com/2020/11/11/rural-hospitals-cant-afford-freezers-to-store-pfizer-covid19-vaccine/. Published November 11, 2020. Accessed February 26, 2022.
150. Opel DJ, Lo B, Peek ME. Addressing Mistrust About COVID-19 Vaccines Among Patients of Color. *Ann Intern Med*. 2021;174(5):698-700. doi:10.7326/M21-0055
151. Kreps S, Dasgupta N, Brownstein JS, Hswen Y, Kriner DL. Public attitudes toward COVID-19 vaccination: The role of vaccine attributes, incentives, and misinformation. *Npj Vaccines*. 2021;6(1):1-7. doi:10.1038/s41541-021-00335-2
152. Chiappini E, Parigi S, Galli L, et al. Impact that the COVID-19 pandemic on routine childhood vaccinations and challenges ahead: A narrative review. *Acta Paediatr Oslo Nor 1992*. 2021;110(9):2529-2535. doi:10.1111/apa.15949
153. Paina L, Peters DH. Understanding pathways for scaling up health services through the lens of complex adaptive systems. *Health Policy Plan*. 2012;27(5):365-373. doi:10.1093/heapol/czr054
154. de Meyrick J. The Delphi method and health research. *Health Educ*. 2003;103(1):7-16. doi:10.1108/09654280310459112
155. Cantrill JA, Sibbald B, Buetow S. The Delphi and nominal group techniques in health services research. *Int J Pharm Pract*. 1996;4(2):67-74. doi:10.1111/j.2042-7174.1996.tb00844.x
156. Burki TK. Cancer care in the time of COVID-19. *Lancet Oncol*. 2020;21(5):628. doi:10.1016/S1470-2045(20)30201-1
157. Henke O. Cancer care in East Africa amidst the Covid-19 pandemic. *Int J Cancer*. doi:10.1002/ijc.33611
158. Patel B. Impact of the COVID-19 Pandemic on Administration of Selected Routine Childhood and Adolescent Vaccinations — 10 U.S. Jurisdictions, March–September 2020. *MMWR Morb Mortal Wkly Rep*. 2021;70. doi:10.15585/mmwr.mm7023a2

159. Kruk ME, Myers M, Varpilah ST, Dahn BT. What is a resilient health system? Lessons from Ebola. *Lancet Lond Engl*. 2015;385(9980):1910-1912. doi:10.1016/S0140-6736(15)60755-3
160. Jones SA, Gopalakrishnan S, Ameh CA, White S, van den Broek NR. "Women and babies are dying but not of Ebola": the effect of the Ebola virus epidemic on the availability, uptake and outcomes of maternal and newborn health services in Sierra Leone. *BMJ Glob Health*. 2016;1(3):e000065. doi:10.1136/bmjgh-2016-000065
161. Hogan AB, Jewell BL, Sherrard-Smith E, et al. Potential impact of the COVID-19 pandemic on HIV, tuberculosis, and malaria in low-income and middle-income countries: a modelling study. *Lancet Glob Health*. 2020;8(9):e1132-e1141. doi:10.1016/S2214-109X(20)30288-6
162. Schoch-Spana M. An Epidemic Recovery Framework to Jump-start Analysis, Planning, and Action on a Neglected Aspect of Global Health Security. *Clin Infect Dis Off Publ Infect Dis Soc Am*. 2020;71(9):2516. doi:10.1093/cid/ciaa486
163. Mustafa S, Zhang Y, Zibwowa Z, et al. COVID-19 Preparedness and Response Plans from 106 countries: a review from a health systems resilience perspective. *Health Policy Plan*. 2022;37(2):255-268. doi:10.1093/heapol/czab089
164. Rodriguez DC, Neel AH, Mahendradhata Y, et al. The effects of polio eradication efforts on health systems: a cross-country analysis using the Develop-Distort Dilemma. *Health Policy Plan*. 2021;36(5):707-719. doi:10.1093/heapol/czab044
165. Orenstein WA, Seib K. Beyond vertical and horizontal programs: a diagonal approach to building national immunization programs through measles elimination. *Expert Rev Vaccines*. 2016;15(7):791-793. doi:10.1586/14760584.2016.1165614
166. World Health Organization. WHO vaccine-preventable diseases: monitoring system. 2020 global summary. World Health Organization. Accessed February 26, 2022. https://apps.who.int/immunization_monitoring/globalsummary/indicators/
167. Seawright J, Gerring J. Case Selection Techniques in Case Study Research: A Menu of Qualitative and Quantitative Options. *Polit Res Q*. 2008;61(2):294-308. doi:10.1177/1065912907313077
168. Bekker MPM, Mays N, Kees Helderman J, et al. Comparative institutional analysis for public health: governing voluntary collaborative agreements for public health in England and the Netherlands. *Eur J Public Health*. 2018;28(suppl_3):19-25. doi:10.1093/eurpub/cky158
169. Lijphart A. Comparative Politics and the Comparative Method. *Am Polit Sci Rev*. 1971;65(3):682-693. doi:10.2307/1955513
170. World Health Organization. Disease Outbreak News. World Health Organization. Accessed February 19, 2022. https://www.who.int/emergencies/disease-outbreak-news
171. World Bank. World Bank Country and Lending Groups – World Bank Data Help Desk. Accessed February 19, 2022. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups
172. U.S. Central Intelligence Agency. Liberia - The World Factbook. Accessed February 19, 2022. https://www.cia.gov/the-world-factbook/countries/liberia/

173. U.S. Central Intelligence Agency. Haiti - The World Factbook. The World Factbook. Published February 11, 2022. Accessed February 19, 2022. https://www.cia.gov/the-world-factbook/countries/haiti/
174. Pan American Health Organization. Haiti: Profile of the Health Services System. Published online July 2003. Accessed February 19, 2022. https://www.paho.org/hq/dmdocuments/2010/Health_System_Profile-Haiti_2003.pdf
175. Ministry of Health and Social Welfare. National Health and Social Welfare Policy and Plan 2011–2021. Published online July 2011. Accessed February 19, 2022. http://moh.gov.lr/wp-content/uploads/National-Health-Policy-Plan-MOH-2011-2021.pdf
176. U.S. Agency for International Development, U.S. Department of State. Liberia. ForeignAssistance.gov. Accessed February 19, 2022. https://foreignassistance.gov/cd/liberia/
177. U.S. Agency for International Development, U.S. Department of State. Haiti. ForeignAssistance.gov. Accessed February 19, 2022. https://foreignassistance.gov/cd/haiti/
178. Rowley J. Using case studies in research. *Manag Res News*. 2002;25(1):16-27. doi:10.1108/01409170210782990
179. Nowell LS, Norris JM, White DE, Moules NJ. Thematic Analysis: Striving to Meet the Trustworthiness Criteria. *Int J Qual Methods*. 2017;16(1):1609406917733847. doi:10.1177/1609406917733847
180. Grant MJ, Booth A. A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Inf Libr J*. 2009;26(2):91-108. doi:10.1111/j.1471-1842.2009.00848.x
181. Garritty C, Gartlehner G, Nussbaumer-Streit B, et al. Cochrane Rapid Reviews Methods Group offers evidence-informed guidance to conduct rapid reviews. *J Clin Epidemiol*. 2021;130:13-22. doi:10.1016/j.jclinepi.2020.10.007
182. CEBMa Center for Evidence-Based Management. CEBMa Guideline for Rapid Evidence Assessments in Management and Organizations. Published online 2017. https://www.cebma.org/wp-content/uploads/CEBMa-REA-Guideline.pdf
183. The Public Health National Center for Innovations. The 10 Essential Public Health Services. Published online 2020. Accessed February 19, 2022. https://phnci.org/uploads/resource-files/EPHS-English.pdf
184. U.S. Centers for Disease Control & Prevention. 10 Essential Public Health Services. Centers for Disease Control & Prevention. Published March 18, 2021. Accessed February 19, 2022. https://www.cdc.gov/publichealthgateway/publichealthservices/essentialhealthservices.html
185. Fitter DL, Delson DB, Guillaume FD, et al. Applying a New Framework for Public Health Systems Recovery following Emergencies and Disasters: The Example of Haiti following a Major Earthquake and Cholera Outbreak. *Am J Trop Med Hyg*. 2017;97(4 Suppl):4. doi:10.4269/ajtmh.16-0862
186. Clay LA, Stone KW, Horney JA. Quantifying Disaster Impacts on Local Public Health Agency's Leadership, Staffing, and Provision of Essential Public Health

Services. *Disaster Med Public Health Prep*. Published online August 16, 2021:1-6. doi:10.1017/dmp.2021.193
187. Mainzer HM, Kruger J, Mahany M. Essential Public Health Services Framework: Use for Rebuilding Communities. *Am J Public Health*. 2019;109(S4):S271-S273. doi:10.2105/AJPH.2019.305261
188. Sellers K, Fisher JS, Kuehnert P, Castrucci BC. Meet The Revised 10 Essential Public Health Services: Developed By The Field, Centering Equity. Health Affairs. Published March 25, 2021. https://www.healthaffairs.org/do/10.1377/forefront.20210319.479091/full/
189. *NVivo*. QSR International Pty Ltd.; 2018. https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home?_ga=2.147149623.1834575441.1645928993-1997246167.1645928993
190. Miles MB, Huberman AM, Saldaña J. *Qualitative Data Analysis: A Methods Sourcebook*. 4th ed. SAGE Publications, Inc.; 2022. Accessed February 19, 2022. https://us.sagepub.com/en-us/nam/qualitative-data-analysis/book246128
191. *Stata Statistical Software: Release 17*. StataCorp; 2021.
192. Mills AJ, Durepos G, Wiebe E. Narrative Analysis. In: *Encyclopedia of Case Study Research*. SAGE Publications, Inc.; 2010.
193. D'Amato P. Who was Spartacus? SocialistWorker.org. Published January 15, 2010. Accessed February 20, 2022. http://socialistworker.org/2010/01/15/who-was-spartacus
194. Daut M. When France extorted Haiti – the greatest heist in history. The Conversation. Published June 30, 2020. Accessed February 20, 2022. http://theconversation.com/when-france-extorted-haiti-the-greatest-heist-in-history-137949
195. Ata T. Haiti's Debt to France. ILLUMINATION. Published September 15, 2020. Accessed February 20, 2022. https://medium.com/illumination/haitis-debt-to-france-338bdab8dfa8
196. U.S. Department of State. U.S. Invasion and Occupation of Haiti, 1915-34. Published July 13, 2007. Accessed February 20, 2022. https://2001-2009.state.gov/r/pa/ho/time/wwi/88275.htm
197. Bauduy J. The 1915 U.S. Invasion of Haiti: Examining a Treaty of Occupation. *Soc Educ*. 79(5):244-249.
198. Pezzullo R. *Plunging Into Haiti: Clinton, Aristide, and the Defeat of Diplomacy*. 1st ed. University Press of Mississippi; 2006.
199. Seligmann HJ. The Conquest of Haiti. *The Nation*. https://windowsonhaiti.com/windowsonhaiti/haiti_occupation_series_01.shtml. Published July 10, 1920. Accessed February 20, 2022.
200. Lopez PJ. Clumsy beginnings: from 'modernizing mission' to humanitarianism in the US occupation of Haiti (1915–34). *Environ Plan Econ Space*. 2015;47(11):2240-2256. doi:10.1177/0308518X15598262

201. Reichardt EM. *The Role of the Rockefeller Foundation in the Origins of Treponematosis Control in Haiti, 1915-1927*. Rockefeller Archive Center; 2021:19. https://rockarch.issuelab.org/resources/37949/37949.pdf
202. Office of the Special Envoy to Haiti. *Has Aid Changed? Channelling Assistance to Haiti before and after the Earthquake*. United Nations Office of the Special Envoy for Haiti; 2011.
https://reliefweb.int/sites/reliefweb.int/files/resources/has_aid_changed_en.pdf
203. Kristoff M, Panarelli L. *Haiti: A Republic of NGOs?* United States Institute for Peace; 2010. Accessed February 20, 2022.
https://www.usip.org/sites/default/files/resources/PB%2023%20Haiti%20a%20Republic%20of%20NGOs.pdf
204. de Ville de Goyet C, Sarmiento JP, Grünewald F. *Health Response to the Earthquake in Haiti: Lessons to Be Learned for the next Massive Sudden-Onset Disaster*. Pan American Health Organization; 2010.
https://www.paho.org/disasters/dmdocuments/HealthResponseHaitiEarthq.pdf
205. United Nations Peacekeeping. MINUSTAH Fact Sheet. United Nations Peacekeeping. Accessed February 20, 2022.
https://peacekeeping.un.org/en/mission/minustah
206. UN Security Council. Resolution 1542 (2004) / adopted by the Security Council at its 4961st meeting, on 30 April 2004. Published online April 30, 2004. Accessed February 20, 2022. https://digitallibrary.un.org/record/520532?ln=en
207. Transparency International. Corruption Perceptions Index. Transparency.org. Published 2010. Accessed February 20, 2022.
https://www.transparency.org/en/cpi/2010
208. Kirsch T, Sauer L, Sapir DG. Analysis of the International and US Response to the Haiti Earthquake: Recommendations for Change. *Disaster Med Public Health Prep*. 2012;6(3):200-208. doi:10.1001/dmp.2012.48
209. Pallardy R. 2010 Haiti earthquake. In: *Britannica*. ; 2022. Accessed February 20, 2022. https://www.britannica.com/event/2010-Haiti-earthquake
210. O'Connor MR. Two Years Later, Haitian Earthquake Death Toll in Dispute - Columbia Journalism Review. Columbia Journalism Review. Published January 30, 2016. Accessed February 20, 2022.
https://web.archive.org/web/20160130060859/http://www.cjr.org/behind_the_news/one_year_later_haitian_earthqu.php?page=all
211. Renois C. Haitians angry over slow aid. The Age. Published February 5, 2010. Accessed February 20, 2022.
https://web.archive.org/web/20100207005409/http://www.theage.com.au/world/haitians-angry-over-slow-aid-20100204-ng2g.html
212. Government of the Republic of Haiti. Haiti Earthquake PDNA: Assessment of damage, losses, general and sectoral needs. Published online March 2010. Accessed February 20, 2022.
https://reliefweb.int/sites/reliefweb.int/files/resources/C8D475D8DBEDAEFD49257705000819F9-Full_Report.pdf

213. Gage AD, Leslie HH, Bitton A, et al. Assessing the quality of primary care in Haiti. *Bull World Health Organ*. 2017;95(3):182. doi:10.2471/BLT.16.179846
214. Health Finance & Governance. Haiti Health Workforce Data Audits Lead to Human Resources for Health Improvements. Accessed February 20, 2022. https://www.hfgproject.org/health-workforce-data-audits-lead-improvements-human-resources-health-haiti/
215. World Health Organization. Data Explorer. Global Health Expenditure Database. Accessed February 20, 2022. https://apps.who.int/nha/database/Select/Indicators/en
216. Ministry of Public Health and Population. Expanded Programme on Immunization Comprehensive Multi-Year Plan cMYP-EPI-2011-2015. Published online March 10, 2011. Accessed February 20, 2022. http://caribbeanelections.com/eDocs/strategy/ht_strategy/ht_Immunization_Multiyear_Plan_2011_2015.pdf
217. Cayemittes M, Placide MF, Mariko S, Barrère B, Sévère B, Alexandre C. *Haïti Enquête Mortalité, Morbidité et Utilisation Des Services 2005-06 (Haiti DHS, 2005-06 - Final Report)*. Institut Haïtien de l'Enfance; 2007. Accessed February 20, 2022. https://dhsprogram.com/pubs/pdf/FR192/FR192.pdf
218. What is the Cluster Approach? Humanitarian Response. Published March 31, 2020. Accessed February 20, 2022. https://www.humanitarianresponse.info/en/coordination/clusters/what-cluster-approach
219. Pan American Health Organization. Health Cluster. Accessed February 20, 2022. https://www.paho.org/disasters/dmdocuments/HAITI-Fact-Sheets-05-Health%20Cluster.pdf
220. Bhattacharjee A, Lossio R. *Evaluation of OCHA Response to the Haiti Earthquake*.; 2011. https://www.alnap.org/system/files/content/resource/files/main/evaluation-of-ocha-response-to-the-haiti-earthquake.pdf
221. Weinmeyer R. Pursuing Justice in Haiti's Cholera Epidemic. *AMA J Ethics*. 2016;18(7):178-726. doi:10.1001/journalofethics.2016.18.7.hlaw1-1607
222. Barzilay EJ, Schaad N, Magloire R, et al. Cholera surveillance during the Haiti epidemic--the first 2 years. *N Engl J Med*. 2013;368(7):599-609. doi:10.1056/NEJMoa1204927
223. Cholera Outbreak --- Haiti, October 2010. Accessed February 20, 2022. https://www.cdc.gov/mmwr/preview/mmwrhtml/mm5943a4.htm
224. Burnett EM, Francois J, Sreenivasan N, et al. Oral cholera vaccination coverage after the first global stockpile deployment in Haiti, 2014. *Vaccine*. 2019;37(43):6348-6355. doi:10.1016/j.vaccine.2019.09.018
225. Centers for Disease Control and Prevention (CDC). Cholera in Haiti. Published April 14, 2021. Accessed February 20, 2022. https://www.cdc.gov/cholera/haiti/index.html
226. Lucien MAB, Adrien P, Hadid H, et al. Cholera Outbreak in Haiti: Epidemiology, Control, and Prevention. *Infect Dis Clin Pract*. 2019;27(1):3-11. doi:10.1097/IPC.0000000000000684

227. Rebuilding Haitian Infrastructure and Institutions. World Bank. Published May 3, 2019. Accessed February 20, 2022. https://www.worldbank.org/en/results/2019/05/03/rebuilding-haitian-infrastructure-and-institutions
228. Médecins Sans Frontières. Haiti: An Overview of MSF Operations in 2010. Doctors Without Borders - USA. Published December 20, 2010. Accessed February 26, 2022. https://www.doctorswithoutborders.org/what-we-do/news-stories/news/haiti-overview-msf-operations-2010
229. American Red Cross. Haiti Earthquake: 10-Year Update from the Red Cross. American Red Cross. Published January 2, 2020. Accessed February 20, 2022. https://www.redcross.org/about-us/news-and-events/news/2020/haiti-earthquake-10-year-update-from-the-red-cross.html
230. Knox R. 5 Years After Haiti's Earthquake, Where Did The $13.5 Billion Go? *NPR*. https://www.npr.org/sections/goatsandsoda/2015/01/12/376138864/5-years-after-haiti-s-earthquake-why-aren-t-things-better. Published January 12, 2015. Accessed February 20, 2022.
231. Government of the Republic of Haiti. Action Plan for National Recovery and Development of Haiti: Immediate Key Initiatives for the Future. Published online March 2010. Accessed February 20, 2022. https://www.haitireconstructionfund.org/system/files/Haiti%20Action%20Plan.pdf
232. Ministry of Public Health and Population, National Directorate for Water Supply and Sanitation. National Plan for the Elimination of Cholera in Haiti 2013-2022. Published online 2013. https://www.paho.org/hq/dmdocuments/2013/cholera-haiti-nat-plan-elim-2013-2022.pdf
233. Pan American Health Organization. Vaccination and Immunization. Accessed February 20, 2022. https://www.paho.org/disasters/dmdocuments/HAITI-Fact-Sheets-09-Vaccination.pdf
234. Tohme RA. Measles and Rubella Vaccination Coverage in Haiti, 2012: Implications for Maintaining Measles and Rubella Elimination. In: American Academy of Pediatrics; 2013. Accessed February 20, 2022. https://aap.confex.com/aap/2013/webprogrampress/Paper21493.html
235. Gavi, the Vaccine Alliance. Rapport de l'évaluation conjointe (JA) 2018. Published online 2018. Accessed February 20, 2022. https://www.gavi.org/sites/default/files/document/rapport-de-l-%25C3%25A9valuation-conjointe-haiti-2018pdf.pdf
236. Tohme RA, Francois J, Cavallaro KF, et al. Expansion of Vaccination Services and Strengthening Vaccine-Preventable Diseases Surveillance in Haiti, 2010–2016. *Am J Trop Med Hyg*. 2017;97(4 Suppl):28. doi:10.4269/ajtmh.16-0802
237. Dowell SF, Tappero JW, Frieden TR. Public health in Haiti--challenges and progress. *N Engl J Med*. 2011;364(4):300-301. doi:10.1056/NEJMp1100118
238. Louis FJ, Buteau J, Boncy J, et al. Building and Rebuilding: The National Public Health Laboratory Systems and Services Before and After the Earthquake and Cholera

Epidemic, Haiti, 2009–2015. *Am J Trop Med Hyg*. 2017;97(4 Suppl):21. doi:10.4269/ajtmh.16-0941
239. Ministère de la Santé Publique et de la Population. Plan Stratégique Quinquennal du Réseau National de Laboratoires 2010-2015. Published online July 2010. Accessed February 20, 2022. http://www.mspp.gouv.ht/site/downloads/version%20finalisee%20Plan%20Strategique.pdf
240. Harrison K, Rahimi N, Carolina Danovaro-Holliday M. Factors limiting data quality in the expanded programme on immunization in low and middle-income countries: A scoping review. *Vaccine*. 2020;38(30):4652-4663. doi:10.1016/j.vaccine.2020.02.091
241. Hashimoto K, Adrien L, Rajkumar S. Moving Towards Universal Health Coverage in Haiti. *Health Syst Reform*. 2020;6(1):e1719339. doi:10.1080/23288604.2020.1719339
242. Alexander A. *A History of Colonization on the Western Coast of Africa*.; 1846. https://archive.org/details/historyofcolonizationon00alex/page/n3/mode/2up
243. McDaniel A. Extreme mortality in nineteenth-century Africa: the case of Liberian immigrants. *Demography*. Published online 1992.
244. Schick TW. *Behold the Promised Land: A History of Afro-American Settlers in Nineteenth-Century Liberia*. The Johns Hopkins University Press; 1980.
245. Poindexter HA. The United States Public Health Mission in Liberia. *J Natl Med Assoc*. 1950;42(5):4.
246. Beecher LN. Second World War and U.S. Politico-Economic Expansionism: The Case of Liberia, 1938–45 | Diplomatic History | Oxford Academic. *Dipl Hist*. 2007;3(4):391-412. doi:https://doi.org/10.1111/j.1467-7709.1979.tb00324.x
247. Miller TC. Firestone and the Warlord: Tough Talk in the Jungle. *ProPublica*. https://www.propublica.org/article/firestone-and-the-warlord-chapter-3?token=k6QugzdODUjV_Y9Kbj1hdsw5gEohLUVV. Published 2014. Accessed February 20, 2022.
248. Kieh GK. The Roots of the Second Liberian Civil War. *Int J World Peace*. 2009;26(1):7-30.
249. Bryant takes power in Liberia. *The Guardian*. https://www.theguardian.com/world/2003/oct/14/westafrica. Published October 14, 2003. Accessed February 20, 2022.
250. Kuwonu F. Women: Liberia’s guardians of peace. United Nations. Accessed February 20, 2022. https://www.un.org/africarenewal/magazine/april-2018-july-2018/women-liberia%E2%80%99s-guardians-peace
251. Government of Liberia, World Health Organization. Liberia: Health situation analysis final report, Jul 2002 - Nov 29, 2003. Published online November 29, 2003. Accessed February 20, 2022. https://reliefweb.int/sites/reliefweb.int/files/resources/4A75D4D0C32E16E3C1256DF7004782DC-who-lib-29nov.pdf

252. Academy for Educational Development. Assessment of Health Training Institutions in Liberia. Published online April 2007. Accessed February 20, 2022. https://pdf.usaid.gov/pdf_docs/PNADR384.pdf
253. Global Health Workforce Alliance, World Health Organization. A Universal Truth: No Health Without a Workforce. Published online 2014. Accessed February 20, 2022. https://www.who.int/workforcealliance/knowledge/resources/GHWA-a_universal_truth_report.pdf?ua=1
254. The DHS Program. STATcompiler. Accessed February 20, 2022. https://www.statcompiler.com/en/
255. Ministry of Health and Social Welfare. *National Health Policy and Plan*. Republic of Liberia; 2007. Accessed February 20, 2022. http://moh.gov.lr/wp-content/uploads/National-Health-and-Social-Welfare-Policy-and-Plan-2007-2011.pdf
256. Lee PT, Kruse GR, Chan BT, et al. An analysis of Liberia's 2007 national health policy: lessons for health systems strengthening and chronic disease care in poor, post-conflict countries. *Glob Health*. 2011;7:37. doi:10.1186/1744-8603-7-37
257. Ministry of Health and Social Welfare. *National Health and Social Welfare Financing Policy and Plan 2011-2021*. Republic of Liberia; 2011. Accessed February 20, 2022. https://www.resilientinstitutionsafrica.org/sites/default/files/files/2017/Liberia-National_Health_and_Social_Welfare_Financing_Policy_Plan_2011-2021.pdf
258. Brault MA, Kennedy SB, Haley CA, et al. Factors influencing rapid progress in child health in post-conflict Liberia: a mixed methods country case study on progress in child survival, 2000–2013. *BMJ Open*. 2018;8(10). doi:10.1136/bmjopen-2018-021879
259. Downie R. *The Road to Recovery: Rebuilding Liberia's Health System*. Center for Strategic & International Studies; :24. Accessed February 20, 2022. https://csis-website-prod.s3.amazonaws.com/s3fs-public/legacy_files/files/publication/120822_Downie_RoadtoRecovery_web.pdf
260. U.S. Centers for Disease Control & Prevention. 2014-2016 Ebola Outbreak in West Africa. Centers for Disease Control & Prevention. Published March 17, 2020. Accessed February 20, 2022. https://www.cdc.gov/vhf/ebola/history/2014-2016-outbreak/index.html
261. Timeline. Global Ebola Response. Published March 29, 2014. Accessed February 20, 2022. https://ebolaresponse.un.org/timeline
262. Nyenswah TG, Kateh F, Bawo L, et al. Ebola and Its Control in Liberia, 2014–2015. *Emerg Infect Dis*. 2016;22(2):169. doi:10.3201/eid2202.151456
263. U.S. Mission Liberia. Embassy, MOH Dedicate Emergency Operations Center. U.S. Embassy in Liberia. Published August 21, 2015. Accessed February 20, 2022. https://lr.usembassy.gov/embassy-moh-dedicate-emergency-operations-center/
264. Division of Global Health Protection. Faster, Smarter Outbreak Response in Liberia. Centers for Disease Control & Prevention. Published August 7, 2017. Accessed February 20, 2022. https://www.cdc.gov/globalhealth/healthprotection/fieldupdates/summer-2017/liberia-outbreak-response.html

265. Ebola Response MPTF. Trust Fund Factsheet. Multi-Partner Trust Fund Gateway. Accessed February 20, 2022. https://mptf.undp.org/factsheet/fund/EBO00
266. Clarke A, Blidi N, Yokie J, et al. Strengthening immunization service delivery post Ebola virus disease (EVD) outbreak in Liberia 2015-2017. *Pan Afr Med J*. 2019;33(Suppl 2). doi:10.11604/pamj.supp.2019.33.2.17116
267. Wesseh CS, Najjemba R, Edwards JK, Owiti P, Tweya H, Bhat P. Did the Ebola outbreak disrupt immunisation services? A case study from Liberia. *Public Health Action*. 2017;7(Suppl 1):S82. doi:10.5588/pha.16.0104
268. Zolia Y, Musa E, Wesseh CS, et al. Setting the Scene for Post-Ebola Health System Recovery and Resilience in Liberia: Lessons Learned and the Way Forward. *Health Syst Policy Res*. 2017;4(1). doi:10.21767/2254-9137.100061
269. World Health Organization. *Monitoring the Building Blocks of Health Systems: A Handbook of Indicators and Their Measurement Strategies*. World Health Organization; 2010. https://www.who.int/healthinfo/systems/WHO_MBHSS_2010_full_web.pdf
270. Republic of Liberia. The Economic Stabilization and Recovery Plan. Published online April 2015. Accessed February 20, 2022. https://reliefweb.int/sites/reliefweb.int/files/resources/liberia_-_economic_stabilization_and_recovery_plan_2015-2017.pdf
271. Ministry of Health. *National EPI Strategic Plan (Draft) 2016-2020*. Republic of Liberia; 2016. Accessed February 20, 2022. http://www.africanchildforum.org/clr/policy%20per%20country/2018%20Update/Liberia/liberia_comprehensivemultiyearplan_2016-2020_2016_en.pdf
272. Republic of Liberia. *Joint National Action Plan for Health Security (NAPHS)*. Republic of Liberia; 2018. Accessed February 20, 2022. https://extranet.who.int/sph/sites/default/files/document-library/document/20062018%20Liberia%20NAPHS%20Final%20version.pdf
273. Ministry of Foreign Affairs. *Public Health Law of Liberia as Revised, 2019*.; 2019. https://moh.gov.lr/wp-content/uploads/FINISHED-DRAFT-REVISED-PUBLIC-HEALTH-LAW-REPUBLIC-OF-LIBERIA-2019_Validation.pdf
274. Gavi, the Vaccine Alliance. Liberia. Gavi, the Vaccine Alliance. Accessed February 20, 2022. https://www.gavi.org/programmes-impact/country-hub/africa/liberia
275. Gavi, the Vaccine Alliance. *Joint Appraisal Report 2017*. Gavi, the Vaccine Alliance; 2017. Accessed February 20, 2022. https://www.gavi.org/sites/default/files/document/joint-appraisal-liberia-2017pdf.pdf
276. Gavi, the Vaccine Alliance. Liberia Joint Appraisal Update Report 2018. Published online 2018. Accessed February 20, 2022. https://www.gavi.org/sites/default/files/document/joint-appraisal-liberia-2018pdf.pdf
277. Earle AJ, Sparkes SP. Financing Common Goods for Health in Liberia post-Ebola: Interview with Honorable Cllr. Tolbert Nyenswah. *Health Syst Reform*. 2019;5(4):387-390. doi:10.1080/23288604.2019.1649949
278. UNICEF. *UNICEF Liberia Ebola Outbreak Weekly Situation Report #78*. UNICEF; 2015. https://reliefweb.int/report/liberia/unicef-liberia-ebola-outbreak-weekly-situation-report-78-25-march-2015

279. Wesseh CS, Nagbe T, Kruger J, et al. Integrated disease surveillance and response in Liberia: national expert group meeting, 15-19 September 2015/Surveillance integree des maladies et riposte au Liberia: reunion d'un groupe d'experts national, 15-19 Septembre 2015. *Wkly Epidemiol Rec*. 2016;91(9):112-121.
280. WHO Regional Office for Africa. *Technical Guidelines for Integrated Disease Surveillance and Response in the African Region: Third Edition*. World Health Organization; 2019. Accessed February 20, 2022. https://www.afro.who.int/publications/technical-guidelines-integrated-disease-surveillance-and-response-african-region-third
281. Nagbe T, Williams GS, Rude JM, et al. Lessons learned from detecting and responding to recurrent measles outbreak in Liberia post Ebola-Epidemic 2016-2017. *Pan Afr Med J*. 2019;33(Suppl 2):7. doi:10.11604/pamj.supp.2019.33.2.17172
282. Nagbe T, Naiene JD, Rude JM, et al. The implementation of integrated disease surveillance and response in Liberia after Ebola virus disease outbreak 2015-2017. *Pan Afr Med J*. 2019;33(Suppl 2). doi:10.11604/pamj.supp.2019.33.2.16820
283. Ahmed K, Bukhari MAS, Altaf MD, et al. Development and Implementation of Electronic Disease Early Warning Systems for Optimal Disease Surveillance and Response during Humanitarian Crisis and Ebola Outbreak in Yemen, Somalia, Liberia and Pakistan. *Online J Public Health Inform*. 2019;11(2). doi:10.5210/ojphi.v11i2.10157
284. McNamara LA. Ebola Surveillance — Guinea, Liberia, and Sierra Leone. *MMWR Suppl*. 2016;65. doi:10.15585/mmwr.su6503a6
285. Bedford J, Chitnis K, Webber N, et al. Community Engagement in Liberia: Routine Immunization Post-Ebola. *J Health Commun*. 2017;22(sup1):81-90. doi:10.1080/10810730.2016.1253122
286. Ministry of Health. *Revised National Community Health Services Policy*. Republic of Liberia; 2015. Accessed February 20, 2022. https://www.exemplars.health/-/media/files/egh/resources/community-health-workers/liberia/revised-community-health-services-policy-20162021.pdf
287. How Liberia reached zero cases of Ebola virus disease. *Releve Epidemiol Hebd*. 2015;90(21):259-260.
288. Government of Liberia Launches Historic National Health Worker Plan to Reach 1.2 Million. Last Mile Health. Published July 24, 2016. Accessed February 20, 2022. https://lastmilehealth.org/2016/07/24/government-liberia-launches-historic-plan/
289. The Elders. Ellen Johnson Sirleaf. Accessed February 20, 2022. https://theelders.org/sites/default/files/elderBio/Ellen%20Johnson%20Sirleaf%20-%20Mar%202021.pdf
290. Ministry of Health. *Investment Plan for Building a Resilient Health System 2015-2021*. Republic of Liberia; 2015. https://www.resilientinstitutionsafrica.org/sites/default/files/2018-09/%5BLIBERIA%5D%20Investment%20Plan%20for%20Building%20a%20Resilient%20Health%20System%20%282015-2021%29.pdf
291. Gavi, the Vaccine Alliance. *Joint Appraisal Update Report 2019*. Gavi, the Vaccine Alliance; 2019. Accessed February 20, 2022.

https://www.gavi.org/sites/default/files/document/2020/Liberia%20Joint%20Appraisal%202019.pdf
292. Nagbe T, Yealue K, Yeabah T, et al. Integrated disease surveillance and response implementation in Liberia, findings from a data quality audit, 2017. *Pan Afr Med J*. 2019;33(Suppl 2). doi:10.11604/pamj.supp.2019.33.2.17608
293. Streifel C. *How Did Ebola Impact Maternal and Child Health in Liberia and Sierra Leone?* Center for Strategic & International Studies; 2015:26. Accessed February 20, 2022. https://csis-website-prod.s3.amazonaws.com/s3fs-public/legacy_files/files/publication/151019_Streifel_EbolaLiberiaSierraLeone_Web.pdf
294. Chachra D. Care at Scale. *Comment Mag*. Published online August 5, 2021. Accessed February 20, 2022. https://comment.org/care-at-scale/
295. Whitener B, Illner P. Catastrophe Capitalism: An Interview with Peer Illner. The New Inquiry. Published September 13, 2021. Accessed February 20, 2022. https://thenewinquiry.com/catastrophe-capitalism-an-interview-with-peer-illner/
296. Suryanarayan P. The origins of state capacity. Broadstreet Blog. Published October 20, 2021. Accessed February 20, 2022. https://broadstreet.blog/2021/10/20/the-origins-of-state-capacity/
297. World Health Organization. Common goods for health. Accessed February 20, 2022. https://www.who.int/westernpacific/health-topics/common-goods-for-health
298. Noor AM. Country ownership in global health. *PLoS Glob Public Health*. 2022;2(2):e0000113. doi:https://doi.org/10.1371/journal.pgph.0000113
299. Cash-Gibson L. *Integrating Health Services*. World Health Organization; 2018. https://www.who.int/docs/default-source/primary-health-care-conference/linkages.pdf
300. Einav S, Hick JL, Hanfling D, et al. Surge capacity logistics: care of the critically ill and injured during pandemics and disasters: CHEST consensus statement. *Chest*. 2014;146(4 Suppl):e17S-43S. doi:10.1378/chest.14-0734
301. Mounier-Jack S, Griffiths UK, Closser S, Burchett H, Marchal B. Measuring the health systems impact of disease control programmes: a critical reflection on the WHO building blocks framework. *BMC Public Health*. 2014;14:278. doi:10.1186/1471-2458-14-278
302. Data Powered Positive Deviance Initiative. The Data Powered Positive Deviance Handbook. Published online November 25, 2021. Accessed February 20, 2022. https://acceleratorlabs.undp.org/content/dam/acceleratorlabs/publications/DPPD_Handbook_Nov_2021.pdf
303. Topp SM, Schaaf M, Sriram V, et al. Power analysis in health policy and systems research: a guide to research conceptualisation. *BMJ Glob Health*. 2021;6(11):e007268. doi:10.1136/bmjgh-2021-007268
304. World Health Organization. *Integration of Health Care Delivery: Report of a WHO Study Group*. World Health Organization; 1996. Accessed February 27, 2022. https://apps.who.int/iris/handle/10665/38408
305. World Health Organization. Primary health care. World Health Organization. Accessed February 27, 2022. https://www.who.int/health-topics/primary-health-care#tab=tab_1

306. World Health Organization Maximizing Positive Synergies Collaborative Group, Samb B, Evans T, et al. An assessment of interactions between global health initiatives and country health systems. *Lancet Lond Engl*. 2009;373(9681):2137-2169. doi:10.1016/S0140-6736(09)60919-3
307. Wyss K, Doumagoum Moto D, Callewaert B. Constraints to scaling-up health related interventions: the case of Chad, Central Africa. *J Int Dev*. 2003;15(1):87-100. doi:10.1002/jid.967
308. Seshadri SR. Constraints to scaling-up health programmes: a comparative study of two Indian states. *J Int Dev*. 2003;15(1):101-114. doi:10.1002/jid.968
309. Munishi GK. Intervening to address constraints through health sector reforms in Tanzania: some gains and the unfinished business. *J Int Dev*. 2003;15(1):115-131. doi:10.1002/jid.969
310. Atun R, de Jongh TE, Secci FV, Ohiri K, Adeyi O, Car J. Integration of priority population, health and nutrition interventions into health systems: systematic review. *BMC Public Health*. 2011;11(1):780. doi:10.1186/1471-2458-11-780
311. Wallace A, Dietz V, Cairns KL. Integration of immunization services with other health interventions in the developing world: what works and why? Systematic literature review. *Trop Med Int Health TM IH*. 2009;14(1):11-19. doi:10.1111/j.1365-3156.2008.02196.x
312. Wallace AS, Ryman TK, Dietz V. Experiences integrating delivery of maternal and child health services with childhood immunization programs: systematic review update. *J Infect Dis*. 2012;205 Suppl 1:S6-19. doi:10.1093/infdis/jir778
313. Atun R, de Jongh T, Secci FV, Ohiri K, Adeyi O. *Clearing the Global Health Fog: A Systematic Review of the Evidence on Integration of Health Systems and Targeted Interventions*. World Bank Accessed February 27, 2022. https://openknowledge.worldbank.org/handle/10986/5946
314. Atun R, de Jongh T, Secci F, Ohiri K, Adeyi O. A systematic review of the evidence on integration of targeted health interventions into health systems. *Health Policy Plan*. 2010;25(1):1-14. doi:10.1093/heapol/czp053
315. Niessen LW, ten Hove A, Hilderink H, Weber M, Mulholland K, Ezzati M. Comparative impact assessment of child pneumonia interventions. *Bull World Health Organ*. 2009;87(6):472-480. doi:10.2471/blt.08.050872
316. Partapuri T, Steinglass R, Sequeira J. Integrated Delivery of Health Services During Outreach Visits: A Literature Review of Program Experience Through a Routine Immunization Lens | The Journal of Infectious Diseases | Oxford Academic. *J Infect Dis*. 2012;205(Supplement 1). Accessed February 18, 2022. https://academic-oup-com.proxy1.library.jhu.edu/jid/article/205/suppl_1/S20/868074?login=true
317. Guignard A, Praet N, Jusot V, Bakker M, Baril L. Introducing new vaccines in low- and middle-income countries: challenges and approaches. *Expert Rev Vaccines*. 2019;18(2):119-131. doi:10.1080/14760584.2019.1574224
318. Brearley L, Eggers R, Steinglass R, Vandelaer J. Applying an equity lens in the Decade of Vaccines. *Vaccine*. 2013;31 Suppl 2:B103-107. doi:10.1016/j.vaccine.2012.11.088

319. Johri M, Verguet S, Morris SK, et al. Adding interventions to mass measles vaccinations in India. *Bull World Health Organ*. 2016;94(10):718. doi:10.2471/BLT.15.160044
320. United Nations Development Programme. Global Dashboard for Vaccine Equity. United Nations Development Programme. Accessed April 14, 2022. https://data.undp.org/vaccine-equity/
321. Dadari I, Higgins-Steele A, Sharkey A, et al. Pro-equity immunization and health systems strengthening strategies in select Gavi-supported countries. *Vaccine*. 2021;39(17):2434-2444. doi:10.1016/j.vaccine.2021.03.044
322. Mitchell S, Andersson N, Ansari NM, Omer K, Soberanis JL, Cockcroft A. Equity and vaccine uptake: a cross-sectional study of measles vaccination in Lasbela District, Pakistan. *BMC Int Health Hum Rights*. 2009;9(1):S7. doi:10.1186/1472-698X-9-S1-S7
323. Sundaram N, Voo TC, Tam CC. Adolescent HPV vaccination: empowerment, equity and ethics. *Hum Vaccines Immunother*. 2020;16(8):1835-1840. doi:10.1080/21645515.2019.1697596
324. Bishai D, Koenig M, Khan MA. Measles vaccination improves the equity of health outcomes: evidence from Bangladesh. *Health Econ*. 2003;12(5):415-419. doi:10.1002/hec.732
325. Geweniger A, Abbas KM. Childhood vaccination coverage and equity impact in Ethiopia by socioeconomic, geographic, maternal, and child characteristics. *Vaccine*. 2020;38(20):3627-3638. doi:10.1016/j.vaccine.2020.03.040
326. Helleringer S, Abdelwahab J, Vandenent M. Polio supplementary immunization activities and equity in access to vaccination: evidence from the demographic and health surveys. *J Infect Dis*. 2014;210 Suppl 1:S531-539. doi:10.1093/infdis/jiu278
327. Bhatia A, Mahmud A, Fuller A, et al. The Rohingya in Cox's Bazar: When the Stateless Seek Refuge. *Health Hum Rights*. 2018;20(2):105.
328. Colson KE, Zúñiga-Brenes P, Ríos-Zertuche D, et al. Comparative Estimates of Crude and Effective Coverage of Measles Immunization in Low-Resource Settings: Findings from Salud Mesoamérica 2015. *PLOS ONE*. 2015;10(7):e0130697. doi:10.1371/journal.pone.0130697
329. Gavi, the Vaccine Alliance. *2016-2020 Strategy Indicator Definitions*. Gavi, the Vaccine Alliance; 2016. https://www.gavi.org/sites/default/files/document/gavi-2016-2020-strategy-indicator-definitionspdf.pdf
330. Arsenault C, Harper S, Nandi A, Rodríguez JMM, Hansen PM, Johri M. An equity dashboard to monitor vaccination coverage. *Bull World Health Organ*. 2017;95(2):128. doi:10.2471/BLT.16.178079
331. World Health Organization. *Health Equity Assessment Toolkit: Technical Notes*. World Health Organization; 2017. Accessed February 27, 2022. Health Equity Assessment Toolkit Built-in Database Edition TECHNICAL NOTES
332. Arambepola R, Yang Y, Hutchinson K, et al. Using geospatial models to map zero-dose children: factors associated with zero-dose vaccination status before and after a mass measles and rubella vaccination campaign in Southern province, Zambia. *BMJ Glob Health*. 2021;6(12):e007479. doi:10.1136/bmjgh-2021-007479

333. Immunization Action Coalition. DTaP, Tdap, and Td Catch-up Vaccination Recommendations by Prior Vaccine History and Age. Published online March 2020. Accessed February 27, 2022. https://www.immunize.org/catg.d/p2055.pdf
334. World Health Organization. Diphtheria vaccine: WHO position paper – August 2017. *Wkly Epidemiol Rec*. 2017;31(92):417-436.
335. World Health Organization. Measles vaccines: WHO position paper – April 2017. *Wkly Epidemiol Rec*. 2017;17:205-227.
336. Hagan JE, Greiner A, Luvsansharav UO, et al. Use of a Diagonal Approach to Health System Strengthening and Measles Elimination after a Large Nationwide Outbreak in Mongolia. *Emerg Infect Dis*. 2017;23(Suppl 1):S77. doi:10.3201/eid2313.170594
337. Mmanga K, Mwenyenkulu TE, Nkoka O, Ntenda PAM. Tracking immunization coverage, dropout and equity gaps among children ages 12–23 months in Malawi – bottleneck analysis of the Malawi Demographic and Health Survey. *Int Health*. Published online June 21, 2021:ihab038. doi:10.1093/inthealth/ihab038
338. Koh HK, Gellin BG. Measles as Metaphor-What Resurgence Means for the Future of Immunization. *JAMA*. 2020;323(10):914-915. doi:10.1001/jama.2020.1372
339. Measles and Rubella Initiative, American Red Cross, Centers for Disease Control and Prevention, UNICEF, United Nations Foundation, World Health Organization. *Measles and Rubella Strategic Framework 2021-2030*. World Health Organization Accessed February 27, 2022. https://apps.who.int/iris/bitstream/handle/10665/339801/9789240015616-eng.pdf?sequence=1
340. Durrheim DN, Crowcroft NS, Strebel PM. Measles – The epidemiology of elimination. *Vaccine*. 2014;32(51):6880-6883. doi:10.1016/j.vaccine.2014.10.061
341. World Health Organization. Worldwide measles deaths climb 50% from 2016 to 2019 claiming over 207,500 lives in 2019. World Health Organization. Published November 12, 2020. Accessed February 27, 2022. https://www.who.int/news/item/12-11-2020-worldwide-measles-deaths-climb-50-from-2016-to-2019-claiming-over-207-500-lives-in-2019
342. Guglielmi G. Measles erases immune ‘memory’ for other diseases. *Nature*. https://www.nature.com/articles/d41586-019-03324-7. Published October 31, 2019. Accessed February 27, 2022.
343. Arsenault C, Johri M, Nandi A, Mendoza Rodríguez JM, Hansen PM, Harper S. Country-level predictors of vaccination coverage and inequalities in Gavi-supported countries. *Vaccine*. 2017;35(18):2479-2488. doi:10.1016/j.vaccine.2017.03.029
344. Arsenault C, Harper S, Nandi A, Mendoza Rodríguez JM, Hansen PM, Johri M. Monitoring equity in vaccination coverage: A systematic analysis of demographic and health surveys from 45 Gavi-supported countries. *Vaccine*. 2017;35(6):951-959. doi:10.1016/j.vaccine.2016.12.041
345. Age, criminal careers, and population heterogeneity: specification and estimation of a nonparametric, mixed Poisson model. *Criminology*. 1993;31(3):327-362.

346. Nagin DS, Odgers CL. Group-based trajectory modeling in clinical research. *Annu Rev Clin Psychol*. 2010;6:109-138. doi:10.1146/annurev.clinpsy.121208.131413
347. Nagin DS, Odgers CL. Group-based trajectory modeling in developmental science. In: *Handbook of Developmental Research Methods*. The Guilford Press; 2012:464-480.
348. Nagin DS. Group-based Trajectory Modeling and Criminal Career Research. *J Res Crime Delinquency*. 2016;53(3):356-371.
349. Proulx CM, Ermer AE, Kanter JB. Group-Based Trajectory Modeling of Marital Quality: A Critical Review. *J Fam Theory Rev*. 2017;9(3):307-327. doi:10.1111/jftr.12201
350. Nguefack HLN, Pagé MG, Katz J, et al. Trajectory Modelling Techniques Useful to Epidemiological Research: A Comparative Narrative Review of Approaches. *Clin Epidemiol*. 2020;12:1205. doi:10.2147/CLEP.S265287
351. Nagin DS. *Group-Based Modeling of Development*. 1st ed. Harvard University Press; 2005. Accessed February 27, 2022. https://www.hup.harvard.edu/catalog.php?isbn=9780674016866
352. Nagin DS. Group-based trajectory modeling: an overview. *Ann Nutr Metab*. 2014;65(2-3):205-210. doi:10.1159/000360229
353. Sweeten G. Group-Based Trajectory Models. In: Bruinsma G, Weisburd D, eds. *Encyclopedia of Criminology and Criminal Justice*. Springer; 2014:1991-2003. doi:10.1007/978-1-4614-5690-2_479
354. Aktaş S, Finch SJ. Project MUSE - Group-Based Trajectory Modeling of Longitudinal International Infant Mortality Rates. *Popul Rev*. 2014;53(2). Accessed February 27, 2022. https://muse.jhu.edu/article/562362/pdf?casa_token=olSfKjRTJIYAAAAA:QuJgrumAecA3bjDHSvNb9bOI9G0yz6Lcdf-zYvfRdz6PvQNy2cX_W_MEP3IWt8xV8O9RN1FCu7k
355. Morris NA, Slocum LA. Estimating Country-Level Terrorism Trends Using Group-Based Trajectory Analyses: Latent Class Growth Analysis and General Mixture Modeling. *J Quant Criminol*. 2012;28(1):103-139. doi:10.1007/s10940-011-9158-2
356. English M, Schellenberg J, Todd J. Assessing health system interventions: key points when considering the value of randomization. *Bull World Health Organ*. 2011;89(12):907. doi:10.2471/BLT.11.089524
357. Latent Variable. In: *Encyclopedia of Research Design*. SAGE Publications, Inc.; 2010. doi:10.4135/9781412961288.n213
358. Casey RM. Global Routine Vaccination Coverage, 2015. *MMWR Morb Mortal Wkly Rep*. 2016;65. doi:10.15585/mmwr.mm6545a5
359. Weller BE, Bowen NK, Faubert SJ. Latent Class Analysis: A Guide to Best Practice. *J Black Psychol*. 2020;46(4):287-311. doi:10.1177/0095798420930932
360. Sodha SV, Dietz V. Strengthening routine immunization systems to improve global vaccination coverage. *Br Med Bull*. 2015;113(1):5-14. doi:10.1093/bmb/ldv001
361. World Health Organization. *Working Together: An Integration Resource Guide for Immunization Services Throughout the Life Course*. World Health Organization; 2018.

362. Jones BL, Nagin DS. A Stata Plugin for Estimating Group-Based Trajectory Models. Published online May 21, 2012. Accessed February 27, 2022. https://ssrc.indiana.edu/doc/wimdocs/2013-03-29_nagin_trajectory_stata-plugin-info.pdf
363. International Center for Equity in Health. Absolute and relative measures of inequality. International Center for Equity in Health | Pelotas. Accessed February 28, 2022. https://equidade.org/siicix
364. Soper D. *Free A-Priori Sample Size Calculator for Structural Equation Models*.; 2022. Accessed February 28, 2022. https://www.danielsoper.com/statcalc/calculator.aspx?id=89
365. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Lawrence Erlbaum Associates; 1988. Accessed February 28, 2022. https://www.taylorfrancis.com/books/mono/10.4324/9780203771587/statistical-power-analysis-behavioral-sciences-jacob-cohen
366. Christopher Westland J. Lower bounds on sample size in structural equation modeling. *Electron Commer Res Appl*. 2010;9(6):476-487. doi:10.1016/j.elerap.2010.07.003
367. Brownwright TK, Dodson ZM, van Panhuis WG. Spatial clustering of measles vaccination coverage among children in sub-Saharan Africa. *BMC Public Health*. 2017;17(1):957. doi:10.1186/s12889-017-4961-9
368. Mantel C, Cherian T. New immunization strategies: adapting to global challenges. *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz*. 2020;63(1):25. doi:10.1007/s00103-019-03066-x
369. Mihigo R, Anya B, Okeibunor J, et al. African vaccination week as a vehicle for integrated health service delivery. *BMC Health Serv Res*. 2015;15:358. doi:10.1186/s12913-015-0989-7
370. Ropero-Álvarez AM, Kurtis HJ, Danovaro-Holliday MC, Ruiz-Matus C, Tambini G. Vaccination Week in the Americas: an opportunity to integrate other health services with immunization. *J Infect Dis*. 2012;205 Suppl 1:S120-125. doi:10.1093/infdis/jir773
371. Grabowsky M, Farrell N, Hawley W, et al. Integrating insecticide-treated bednets into a measles vaccination campaign achieves high, rapid and equitable coverage with direct and voucher-based methods. *Trop Med Int Health TM IH*. 2005;10(11):1151-1160. doi:10.1111/j.1365-3156.2005.01502.x
372. Ryman TK, Wallace A, Mihigo R, et al. Community and Health Worker Perceptions and Preferences Regarding Integration of Other Health Services With Routine Vaccinations: Four Case Studies. *J Infect Dis*. 2012;205(suppl_1):S49-S55. doi:10.1093/infdis/jir796
373. Ortiz JR, Perut M, Dumolard L, et al. A global review of national influenza immunization policies: Analysis of the 2014 WHO/UNICEF Joint Reporting Form on immunization. *Vaccine*. 2016;34(45):5400-5405. doi:10.1016/j.vaccine.2016.07.045
374. Kulkarni S, Harvey B, Prybylski D, Jalloh MF. Trends in classifying vaccine hesitancy reasons reported in the WHO/UNICEF Joint Reporting Form, 2014–2017:

Use and comparability of the Vaccine Hesitancy Matrix. *Hum Vaccines Immunother*. 2021;17(7):2001. doi:10.1080/21645515.2020.1859319
375. Pan American Health Organization. Frequent Asked Questions (FAQs): WHO-UNICEF Joint Reporting Form on Immunization (JRF) and Estimates of National Immunization Coverage (WUENIC). Published online 2020. https://iris.paho.org/bitstream/handle/10665.2/52625/PAHOFPLIM200015_eng.pdf?sequence=1&isAllowed=y
376. Patenaude B, Odihi D, Sriudomporn S, Mak J, Watts E, de Broucker G. *A Standardized Approach for Measuring Multi-Dimensional Equity in Vaccination Coverage, Cost-of-Illness, and Health Outcomes: Evidence from the Vaccine Economics Research for Sustainability & Equity (VERSE) Project*. Social Science Research Network; 2021. doi:10.2139/ssrn.3945450
377. Loughran T, Nagin DS. Finite Sample Effects in Group-Based Trajectory Models. *Sociol Methods Res*. 2006;35(2):250-278. doi:10.1177/0049124106292292
378. Ota MOC, Badur S, Romano-Mazzoti L, Friedland LR. Impact of COVID-19 pandemic on routine immunization. *Ann Med*. 53(1). Accessed February 18, 2022. https://www-tandfonline-com.proxy1.library.jhu.edu/doi/full/10.1080/07853890.2021.2009128
379. Wheatley MJ, Kellner-Rogers M. Bringing life to organizational change. *J Strateg Perform Meas*. Published online 1998. https://www.margaretwheatley.com/wp-content/uploads/2014/12/Bringing-Life-to-Organizational-Change.pdf
380. Abimbola S. The uses of knowledge in global health. *BMJ Glob Health*. 2021;6(4):e005802. doi:10.1136/bmjgh-2021-005802

SANJANA JAYALAKSHMI RAVI
CURRICULUM VITAE

EDUCATION

PhD Candidate | **The Johns Hopkins University** | **2022 (anticipated)**

- Concentration: Health Systems (Department of International Health)
- Dissertation focus: vaccine delivery during outbreaks, integrated vaccine delivery, and vaccine equity

Master of Public Health | **University of Pittsburgh** | **2013**

- Concentration: Infectious Disease Management, Intervention, and Community Practice
- Thesis: The Impact of Transfusion-Transmissible Viruses on Blood Product Management in the United States

Bachelor of Arts | **Saint Louis University** | **2011**

- Major: Biology
- Minor: Theological Studies

SKILLS

- Technical: Qualitative methods and research design, policy writing and analysis, monitoring and evaluation
- Software: Microsoft Office, Stata, NVivo, Google Workspace
- Languages: English (native speaker), Spanish (intermediate), Telugu (elementary)

EXPERIENCE

Senior Research Associate | **The Johns Hopkins Center for Health Security** | **May 2013-Present**

- Lead and support innovative research on global health security, public health and healthcare preparedness, health systems strengthening, community engagement, and risk communication
- Identify and evaluate best practices and lessons learned to inform programs, strategies, and policy recommendations for strengthening public health and healthcare responses to outbreaks and natural disasters
- Prepare grant proposals, issue briefs, and technical whitepapers
- Draft summary reports, scholarly publications, and communication materials
- Present research findings at relevant conferences, webinars, and meetings

- Member, NSF CONVERGE Working Group: Readying Populations for the COVID-19 Vaccine; Member, CommuniVax Coalition to Strengthen the Community's Involvement in an Equitable Vaccination Rollout
- Managed of a team of seven research associates, assistants, and interns (2017- 2018)
- Major accomplishments:
  - Providing technical assistance around health security capacity-building to partners across West Africa, South America, and Pakistan
  - Co-designed a checklist for strengthening health system resilience
  - Coordinated high-level meetings with government officials and thought leaders in public health, healthcare, and national security representing the U.S., Singapore, Malaysia, Indonesia, and India
  - Leading independent research efforts around last mile challenges in vaccine delivery during outbreaks, vaccine equity, healthcare worker needs during conflict, and epidemic recovery

Consultant	**African Constituency Bureau for the Global Fund**	**October 2020-December 2020**

- Performed a rapid review of the latest evidence on health security and COVID-19
- Formulated policy options for the Global Fund to strengthen country responses to major endemic and epidemic health threats (HIV/AIDS, malaria, TB, COVID-19)
- Synthesized recommendations for maximizing health security investments in Africa

Consultant	**World Health Organization**	**November 2019-March 2020; October 2021-Present**

- Supported development of a value attribution framework for evaluating vaccines against antimicrobial-resistant (AMR) pathogens
- Editor for a *Lancet* special series on mass gatherings medicine and reports on preparations for the Tokyo 2020 and Beijing 2022 Olympic Games
- Support development of a mass gatherings operational framework

Fellow	**Synthetic Biology Leadership Excellence Accelerator Program**	**January 2015-January 2016**

- Examined the legal, ethical, and societal impacts of synthetic biology research & practice

- Developed a strategic action plan for harnessing synthetic biology to strengthen U.S. national capacities for responding to biological threats

Global Impact Fellow	**Unite for Sight**	**March 2013**

- Raised over $2,000 to fund cataract surgeries for economically disadvantaged patients
- Performed pre-clinical screenings for patients at El Centro de Salud Integral ZOE in Tegucigalpa, Honduras
- Traveled to medically underserved communities across Honduras to deliver eyeglasses and provide visual acuity consultations

Graduate Research Assistant	**World History Center, University of Pittsburgh**	**September 2012-April 2013**

- Researched and developed novel applications of social science theory to guide construction of a world-historical database
- Created an interdisciplinary methodological framework to guide studies of human populations

Research Assistant	**Public Health Computational and Operations Group, University of Pittsburgh**	**September 2011-December 2012**

- Conducted independent research on:
    - Uses of real-time RT-PCR as a diagnostic tool for nosocomial viral gastroenteritis
    - Reduction of fomite transmission of nosocomial pathogens
    - Clinical outcomes and economic burdens of surgical site infections

Assessment Aide	**Center for Aging and Population Health, University of Pittsburgh**	**October 2011-April 2012**

- Traveled to sites throughout southwest Pennsylvania to evaluate the effectiveness of a geriatric health program
- Checked study participants' vital signs and conducted physical performance batteries

Project Lead & Volunteer	Project LEAN, Young Women's Christian Association of St. Louis	January 2009-May 2011

- Co-founded and ran a health & wellness program for women enrolled in a transitional housing program
- Developed educational materials on nutrition, fitness, and stress management
- Performed wellness assessments on program participants
- Led fitness activities and group discussions on health and well-being

PUBLICATIONS

Peer-Reviewed Publications:

1) Schoch-Spana M, **Ravi SJ**, and Martin EK. Modeling Epidemic Recovery: An Expert Elicitation on Approaches and Issues. *Social Science & Medicine*. 2021. https://doi.org/10.1016/j.socscimed.2021.114554

2) Sell TK, Warmbrod KL, Watson C, Trotochaud M, Martin E, **Ravi SJ**, Balick M, Servan-Schreiber E. Using Prediction Polling to Harness Collective Intelligence for Disease Forecasting. *BMC Public Health*. October 2021.

3) **Ravi SJ,** Warmbrod KL, Barlow A, Cepeda J, Falade-Nwulia OO, Haroz EE, Purnell TS. Why Social Distance Demands Social Justice: Systemic Racism, COVID-19, and Health Security in the United States. *Health Security*. 2021;19:S1.

4) Schoch-Spana M, Brunson EK, Long R, Ruth, A, **Ravi SJ**, Trotochaud M, et al. The public's role in COVID-19 vaccination: Human-centered recommendations to enhance pandemic vaccine awareness, access, and acceptance in the United States. *Vaccine*. 2020. https://doi.org/10.1016/j.vaccine.2020.10.059

5) **Ravi SJ**, Warmbrod KL, Mullen L, Meyer D, Cameron E, Bell J, Bapat P, Paterra M, Machalaba C, Nath I, Gostin LO, James W, George D, Nikkari S, Gozzer E, Tomori O, Makumbi I, and Nuzzo JB. The Value Proposition of the Global Health Security Index. *BMJ Global Health*. 2020;5:e003648.

6) Schoch-Spana M, Brunson EK, Long R, Ruth A, **Ravi SJ**, Trotochaud M, Borio L, Brewer J, Buccina J, Connell N, Hall LL, Kass N, Kirkland A, Koonin L, Larson H, Lu BF, Omer SB, Orenstein WA, Poland GA, Privor-Dumm L, Quinn SC, Salmon D, and White A. The public's role in COVID-19 vaccination: Human-centered recommendations to enhance pandemic vaccine awareness, access, and acceptance in the United States. *Vaccine*. https://dx.doi.org/10.1016%2Fj.vaccine.2020.10.059.

7) Meyer D, Bishai D, **Ravi SJ**, Rashid H, Mahmood SS, Toner E, and Nuzzo JB. A Checklist to Improve Health System Resilience to Infectious Disease Outbreaks and Natural Hazards. *BMJ Global Health*. 2020;5:e002429.

8) Slemp CC, Sisco S, Jean MC, Ahmed MS, Kanarek NF, Erös-Sarnyai M, Gonzalez IA, Igusa T, Lane K, Tirado FP, Tria M, Lin S, Martins VM, **Ravi S**, Kendra JM, Carbone EG, Links JM. Applying an Innovative Model of Disaster Resilience at the Neighborhood Level: The COPEWELL New York City Experience. *Public Health Reports*. 2020. https://doi.org/10.1177%2F0033354920938012.

9) Sell TK, Watson C, Meyer D, Snyder MR, **Ravi SJ**, McGinty EE, Pechta LE, Rose DA, Podgornik MN, and Lubell KM. Zika Inquiries Made to the CDC-INFO System, December 2015–September 2017. *Emerging Infectious Diseases*. 2020 May;26(5):1022-1024.

10) Trotochaud M, Sell TK, **Ravi SJ**, Andrada CI, Nuzzo JB. State by State Implementation of Zika Virus Testing Guidance in the United States in 2017 and 2018. *Preventive Medicine Reports*. 2020. https://doi.org/10.1016/j.pmedr.2020.101097.

11) Brunson EK, Chandler, H, Gronvall, GK, **Ravi S**, Sell TK, Shearer MP, Schoch-Spana ML. The SPARS Pandemic 2025-2028: A Futuristic Scenario to Facilitate Medical Countermeasure Communication. *Journal of International Crisis & Risk Communication Research.* 2020:3(1).

12) Sell T, **Ravi S**, Watson C, Meyer D, Pechta L, Rose D, Lubell K, Podgornik M, Schoch-Spana M. A Public Health Systems View of Risk Communication about Zika. Submitted to *Public Health Reports*. 2020.

13) Schoch-Spana M, Watson C, **Ravi S**, Meyer D, Pechta LE, Rose DA, Lubell KM, Podgornik MN, and Sell TK. Vector Control in Zika-Affected Communities: Local Views on Community Engagement and Public Health Ethics During Outbreaks. *Preventive Medicine Reports*. 2020. Doi: https://doi.org/10.1016/j.pmedr.2020.101059.

14) **Ravi SJ**, Meyer D, Cameron E, Nalabandian M, Pervaiz, B, and Nuzzo JB. Establishing a theoretical foundation for measuring global health security: a scoping review. *BMC Public Health*. 2019:19(954).

15) **Ravi SJ**, Snyder MR, and Rivers CM. Review of International Efforts to Strengthen the Global Outbreak Response System Since the 2014-16 West Africa Ebola Epidemic. *Health Policy and Planning*. January 2019.

16) Nuzzo JB, Meyer D, Snyder MR, **Ravi SJ**, Lapascu A, Souleles J, Andrada CI, and Bishai D. What makes health systems resilient against infectious disease

outbreaks and natural hazards? Results from a scoping review. *BMC Public Health*. 2019:19(1310).

17) Snyder MR and **Ravi SJ.** 1818, 1918, 2018: Two Centuries of Pandemics. *Health Security*. 2018:16(6).

18) Schoch-Spana M, Brunson EK, Chandler H, Gronvall GK, **Ravi S**, Sell TK, and Shearer MP. Recommendations on How to Manage Anticipated Communication Dilemmas Involving Medical Countermeasures in an Emergency. *Public Health Reports*. 2018;133(4)366-378.

19) Sell TK, Watson C, Meyer D, Bane M, **Ravi S**, Pechta LE, Lubell KM, Rose DA. Frequency of Risk-Related News Media Messages in 2016 Coverage of Zika Virus. *Risk Analysis.* January 2018.

20) Schoch-Spana M, Nuzzo JB, **Ravi S**, Biesiadecki L, and Mwaungulu G. The Local Health Department Mandate and Capacity for Community Engagement in Emergency Preparedness: A National View Over Time. *Journal of Public Health Management & Practice*. January 2018.

21) Schoch-Spana M, **Ravi S**, Meyer D, Biesiadecki L, Mwaungulu G. High Performing Local Health Departments Relate their Experiences at Community Engagement in Emergency Preparedness. *Journal of Public Health Management & Practice.* November 2017.

22) Monica Schoch-Spana, Anita Cicero, Amesh Adalja, Gigi Gronvall, Tara Kirk Sell, Diane Meyer, Jennifer B. Nuzzo, **Sanjana Ravi**, Matthew P. Shearer, Eric Toner, Crystal Watson, Matthew Watson, and Tom Inglesby. Global Catastrophic Biological Risks: Toward a Working Definition. *Health Security*. 2017: 15(4)323-28.

23) **Ravi SJ**. Strengthening Health Systems through International Blood Product Sharing Agreements. *Health Security.* 2017: 15(1)110-17.

24) Meyer D, Neibaur E, **Ravi S**, Watson C, Watson M, Shearer M, Cicero A, Inglesby T. *Summary of Key Recommendations: Meeting to Solicit Stakeholder Input on Forthcoming 2017 National Biodefense Strategy.* Johns Hopkins Center for Health Security. June 22, 2017.

25) **Sanjana Ravi** & Amesh Adalja. Strengthening the US Medical Countermeasure Enterprise for Biological Threats. *Health Security*. 2017: 15(1)12-13.

26) Nuzzo JB and **Ravi S**. Strengthening Surveillance for Health Security Threats: The Time is Now. *Health Security*. 2016:14(3):109-10.

27) Gronvall GK, **Ravi S**, Inglesby T, Cicero A. Singapore-Malaysia-Indonesia-US Dialogue on Biosecurity. *Health Security*. 2015:13(6):399-405.

28) Toner ES, **Ravi SJ**, Adalja AA, Waldhorn R, McGinty M, Schoch-Spana M. Exploring Local Collaboration for Emergency Preparedness and Response. *Health Security*. 2015.

29) **Ravi SJ** and Gauldin EM. Sociocultural Dimensions of the Ebola Virus Disease Outbreak in Liberia. *Health Security*. 2014;12(6):301-305.

30) Adalja AA, Sell TK, **Ravi S**, Minton K, and Morhard R. Emergency Preparedness in the 10-Mile Emergency Planning Zone Surrounding Nuclear Power Plants. *Journal of Homeland Security and Emergency Management*. 2014;12(1).

31) Bouri N and **Ravi S**. Going Mobile: How Mobile Personal Health Records Can Improve Health Care During Emergencies. *Journal of Medical Internet Research mHealth and uHealth*. 2014;2(1):e8.

32) Manning P and **Ravi S**. Cross-Disciplinary Theory in Construction of a World-Historical Archive. *Journal of World-Historical Information.* 2013;1(1).

33) Morhard R and **Ravi S.** The Price-Anderson Act and the Role of Congress in Compensating Victims after a Catastrophic Nuclear Disaster. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*. 2012;10(4):340-5.

Commissioned Reports:

1) Schoch-Spana M, Brunson E, Hosangadi D, Long R, **Ravi S**, Taylor M, Trotochaud M, Veenema TG, on behalf of the CommuniVax Coalition. A Waypoint on the Path to Health Equity: COVID-19 Vaccination at Month 11. Baltimore, MD: Johns Hopkins Center for Health Security; 2021.

2) Brunson EK, Schoch-Spana M, Carnes M, Hosangadi D, Long R, **Ravi S**, Taylor M, Trotochaud M, Veenema TG, on behalf of the CommuniVax Coalition. Carrying Equity in COVID-19 Vaccination Forward: Guidance Informed by Communities of Color. Baltimore, MD: Johns Hopkins Center for Health Security; 2021.

3) Schoch-Spana M, Brunson E, Hosangadi D, Long R, **Ravi S**, Taylor M, Trotochaud M, Veenema TG on behalf of the Working Group on Equity in COVID-19. Equity in Vaccination: A Plan to Work with Communities of Color Toward COVID-19 Recovery and Beyond. Baltimore, MD: Johns Hopkins Center for Health Security; 2021.

4) Schoch-Spana M, Brunson E, Long R, **Ravi S**, Ruth A, Trotochaud M on behalf of the Working Group on Readying Populations for COVID-19 Vaccine. The Public's Role in COVID-19 Vaccination: Planning Recommendations Informed by Design

Thinking and the Social, Behavioral, and Communication Sciences. The Johns Hopkins Center for Health Security. Published in July 2020.

5) Elizabeth E. Cameron, Jennifer B. Nuzzo, Jessica A. Bell, Michelle Nalabandian, John O'Brien, Avery League, **Sanjana Ravi**, Diane Meyer, Michael Snyder, Lucia Mullen, and Lane Warmbrod. Global Health Security Index: Building Collective Action and Accountability. Published in October 2019.

6) Watson C, Bruns R, Hosangadi D, Martin E, Meyer D, **Ravi S**. Influenza Vaccines 101: An Overview of Seasonal Influenza for Decision Makers (available upon request). Submitted to the World Health Organization in January 2020.

7) Mullen L, **Ravi S**, Kobokovich A, et al. Deliberate Use of Biological and Chemical Agents: WHO Guidance on Public Health Preparedness and Response. Submitted to Chatham House & the World Health Organization in September 2019.

8) **International Vaccine Access Center.** Supporting Immunization Decision-Making in Low- and Lower-Middle-Income Countries. Submitted to the Wellcome Trust in July 2019. Available upon request.

9) Schoch-Spana M, Hurtado C, Meyer D, Moore-Sheeley, K, **Ravi S**, Snyder M. Risk Communication Strategies for the Very Worst of Cases. The Johns Hopkins Center for Health Security. Published in March 2019.

10) **Ravi S**, Gronvall GK, Inglesby T, and Cicero A. US-India Strategic Dialogue on Biosecurity: Report from the Fourth Dialogue Session. The Johns Hopkins Center for Health Security. Published in April 2018.

11) **Ravi S**, Gronvall GK, Inglesby T, and Cicero A. US-India Strategic Dialogue on Biosecurity: Report from the Third Dialogue Session. The Johns Hopkins Center for Health Security. Published in December 2017.

12) Sell TK, Watson C, Meyer D, Ravi SJ, Pechta L, Lubell K, Rose DA. Persuasive Communication About Risks and Responses to a Public Health Threat: An Analysis of Public Health Communication During the Zika Response. The Johns Hopkins Center for Health Security. Completed in 2017.

13) Schoch-Spana M, Brunson EK, Sell TK, Gronvall GK, Shearer MP, **Ravi S**, Chandler H. The SPARS Pandemic: A Futuristic Scenario for Public Health Risk Communicators. The Johns Hopkins Center for Health Security. Published in October 2017.

14) **Ravi S,** Inglesby T, and Gronvall GK. US-India Strategic Multilateral Dialogue on Biosecurity: Report from the Second Dialogue Session. The Johns Hopkins Center for Health Security. Published in May 2017.

15) Gronvall, GK, **Ravi S**, Inglesby T, and Cicero A. US-India Strategic Multilateral Dialogue on Biosecurity: Report from the First Dialogue Session. UPMC Center for Health Security. Published in October 2016.

16) Schoch-Spana M, Gronvall GK, Brunson E, Sell TK, **Ravi S**, Shearer MP, Collins H. How to Steward Medical Countermeasures and Public Trust in an Emergency: A Communication Casebook for FDA and its Public Health Partners. UPMC Center for Health Security. Published in June 2016.

17) Cicero A, **Ravi S**, Gronvall GK, and Inglesby T. Strategic Multilateral Dialogue on Biosecurity: Report on the Second Dialogue Session Held between the United States, Singapore, Malaysia, and Indonesia. UPMC Center for Health Security. Published in January 2016.

18) Cicero A, **Ravi S**, Gronvall GK, and Inglesby T. Strategic Multilateral Dialogue on Biosecurity: Report on the First Dialogue Session Held between the United States, Singapore, Malaysia, and Indonesia. UPMC Center for Health Security. Published in July 2015.

19) Gronvall GK, **Ravi S**, Cicero A, and Inglesby T. Singapore-US Strategic Dialogue on Biosecurity: Report from the Second Dialogue Session. UPMC Center for Health Security. Published in December 2014.

20) Gronvall GK, **Ravi S**, Morhard R, Cicero A, and Inglesby T. Singapore-US Strategic Dialogue on Biosecurity. UPMC Center for Health Security. Published in July 2014.

21) Gronvall GK, **Ravi SJ**, Hansen MB, Morhard R. Alfred P. Sloan Foundation: An Evaluation of the Synthetic Biology Grantmaking Program – Strategy, Organization, and Impact. UPMC Center for Health Security. Published in February 2014.

22) Schoch-Spana M, Bouri N, Minton K, Morhard R, Norwood A, **Ravi S**, Sell TK. Mass Population Displacement after a Nuclear Terrorist Attack: How to Hasten and Strengthen the Recovery of Uprooted Communities. UPMC Center for Health Security. Published in December 2013.

Editorial & Peer Review Activities:

Associate Editor, *Health Security*

- Special issue editor, Systemic Racism and U.S. Health Security During the COVID-19 Pandemic (Volume 19, Issue S1, June 2021)
- Special issue editor, Building the Evidence Base for Global Health Security Implementation (Volume 16, Issue S1, December 2018)
- Special feature editor, Surveillance and Health Security: Building the New Systems We Need to Detect and Manage Health Threats (Volume 14, Issue 3, June 2016)

Peer reviewer:

- *American Journal of Tropical Medicine & Hygiene*
- *BMJ Global Health*
- *Health Policy & Planning*
- *Health Security*
- *The Lancet*
- *Vaccine*
- Special Report on Human Security (United Nations Development Programme)

Editor, COVID-19 Vaccine Development, Policy, and Public Perception in the United States (weekly newsletter)

Media & Public Speaking:

Sanjana Ravi. Amid Coronavirus Spread, Host Countries Ignore Refugee Health at Their Own Peril. Published in *Foreign Policy*. March 27, 2020.

Epidemics and Pandemics: Lessons from the Past, Coordinating for the Future (panel discussion moderated by Dr. Céline Gounder; also featuring Drs. Ronald Waldman and John Brownstein). April 8, 2021. Available here.

Whitepapers:

1) **Sanjana J. Ravi** & Amor A. Menezes. Toward a Synthetic Biology Blueprint for Countering Biological Threats to the United States. Published in June 2017.

2) **Sanjana Ravi**, Nicola Patron, Ted Fjällman, and Karen Ingram. Technology Doesn't Sound Like the Problem. Synthetic Biology Leadership Excellence Accelerator Program. Published in March 2015.

Blog Posts:

1) On Statelessness and Health Security. *The Bifurcated Needle.* July 7, 2015.

2) Counterfeit Medicines and Global Health Security. *The Bifurcated Needle*. May 13, 2015.

3) 2015: The Year of Global Health Security, Millennium Development Goals, and Neglected Tropical Diseases. *The Bifurcated Needle*. March 4, 2015.