Effective Foreign Aid: Evidence from Gavi's Vaccine Program*

Gauri Kartini Shastry† and Daniel L. Tortorice‡

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Abstract

Gavi, the Vaccine Alliance has provided over US$13 billion in funding for vaccination expansion in low-income countries since its founding in 1999. We exploit the differential timing in Gavi support across countries and vaccines to estimate the program's effects. We find that, on average, Gavi's support of a vaccine increased coverage rates by 3 percentage points and reduced child mortality from related causes by between 0.5 and 2 children per 1,000 live births. We estimate these improvements saved between 825,000 and 3.3 million lives at a cost ranging from US $3,940 to US $15,757 per life saved. Given the relatively low cost of Gavi's programs, we argue that Gavi represents a particularly effective form of foreign aid. As Gavi's programs are tightly linked to desirable development outcomes and can be rigorously evaluated, our results provide support for the broader notion that careful structuring of foreign aid programs can be substantially beneficial for low-income countries.

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† Department of Economics, Wellesley College, 106 Central St, Wellesley MA, 02481, gshastry@wellesley.edu, 1 781 283 2382

‡ Department of Economics and Accounting, College of the Holy Cross, 1 College St, Worcester MA, 01610, dtortori@holycross.edu, 1 508 793 3873

I Introduction

One of the most pressing questions in economics is what can be done to improve economic and social outcomes in the world's poorest countries. Perhaps the most notable mechanism at the world's disposal to achieve these goals is foreign aid, the transfer of monetary resources from high-income countries to low-income countries. In 2018, OECD countries spent US$28 billion on official development assistance.[1] This paper studies the impact of foreign aid distributed through Gavi, the Vaccine Alliance (formerly the Global Alliance for Vaccine and Immunisation), the primary vehicle for aid targeting vaccine coverage in developing countries.

Despite the importance and urgency of understanding aid's effects, there is considerable debate as to what, if any, positive impact aid has on economic growth in recipient countries.[2] For example, a highly influential paper, Burnside and Dollar (2000), documented a positive link between foreign aid and economic growth when recipient countries have good underlying economic policies. However, subsequent work argued that these and similar results were sensitive to various assumptions (Easterly et al., 2004; Roodman, 2007). The debate also plays out in the popular press; a recent New York Times editorial argued for revamping foreign aid, by shifting decision-making to local communities, citing research that aid does more harm than good.[3] When turning from economic growth to health, the literature is generally more optimistic, but still not conclusive. For example, multiple papers find that aid reduces infant mortality (Arndt et al., 2015; Mishra and Newhouse, 2009; Kotsadam et al., 2018), while Mukherjee and Kizhakethalackal (2013) argue that health aid affects infant mortality only for countries with at least a certain level of average education. Qian (2015) points to findings that aid increases conflict (Nunn and Qian, 2014; Crost et al., 2014), casting doubt on the possible positive impact of aid on health, and notes the challenge posed by the lack of comparable health data across countries. Williamson (2008) echoes this pessimism finding no impact of foreign health aid on any life expectancy, child mortality or immunization outcomes.

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[1] https://data.oecd.org/oda/distribution-of-net-oda.htm#indicator-chart

[2] See Mekasha and Tarp (2013), UNU-WIDER (2014), Glennie and Sumner (2016) Ch. 4, and Sachs (2006) for comprehensive surveys on the positive effect aid can have on economic growth, and Doucouliagos and Paldam (2008) and Easterly (2006) for comprehensive surveys of literature finding an insignificant or negative effect of aid on economic growth.

[3] https://www.nytimes.com/2021/02/13/opinion/africa-foreign-aid-philanthropy.html

One way forward may lay in foreign aid programs with a tight link between aid and targeted outcomes, as suggested by Bourguignon and Sundberg (2007), *and* with rigorous systematic evaluation of aid programs (Easterly, 2003; Bates et al. 2007; Banerjee and Duflo, 2011). To this end, we study the impact of Gavi, the Vaccine Alliance (Gavi) an alliance aimed at using the donations of high-income countries to purchase and distribute vaccines to the world's lowest income countries. Vaccination is among the most inexpensive and efficacious public health initiatives (Bloom et al., 2005) and successful vaccination campaigns should be tightly linked with outcomes such as vaccine coverage rates and child mortality from vaccine-preventable diseases. As such, foreign aid that promotes vaccination may stand the best chance of efficiently improving measurable outcomes in low-income countries. Additionally, Gavi is a significant source of foreign aid, having distributed more than US$13 billion in funding for vaccines and vaccine support systems over its history. Today, Gavi is a major source of funding for developing countries to acquire COVID-19 vaccines.

Besides having a close link between program and outcomes, the manner in which Gavi rolled out funding with differential timing across countries and vaccines allows for a systematic, causal evaluation of this unique foreign aid program. In order to identify the impact of Gavi support, we exploit variation across countries, cohorts, and vaccines. While eligibility for Gavi support was determined by a country's level of per-capita GNI in 1998, there is considerable variation within a country in when certain vaccines are introduced with Gavi support, as well as variation within a vaccine in when it is introduced across different countries. As we discuss further below in Section IV.A., this variation stems partly from external forces (e.g., vaccine supply constraints, changes in region-specific WHO recommendations) as well as internal constraints (e.g., the availability of funds to meet Gavi's co-financing requirement). Our identification strategy compares coverage of vaccines funded by Gavi to vaccines not funded by Gavi in a particular country for a particular cohort. Country X vaccine fixed effects account for possibly endogenous decisions to fund certain vaccines in certain countries; country X cohort fixed effects allow for flexible time-varying country characteristics; and vaccine X cohort fixed effects account for global time-varying vaccine characteristics (such as global supply or demand shocks).

To develop some intuition for our identification strategy, consider the case of two African countries, Niger and Senegal. Senegal received funding from Gavi for the measles-rubella (MR)

vaccine beginning in 2013 while Niger never received funding for the MR vaccine and did not receive funding for the measles vaccine until 2019. Neither country received Gavi funding for the BCG vaccine. According to survey estimates, between 2011 and 2015 Senegal increased coverage for measles-containing vaccines by 5.6 percentage points. At the same time, Senegal increased coverage of the BCG vaccine by 1.8 percentage points. Subtracting these two measures we could estimate the effect of Gavi's program as increasing measles coverage by 3.8 percentage points. However, it is not obvious that measles and BCG coverage rates would trend in the same manner absent Gavi intervention. To estimate the expected increase in measles coverage relative to BCG absent Gavi intervention, we use Niger as a control country. Niger increased measles and BCG coverage by the same amount (7.4 percentage points) over the same time period. Assuming that absent Gavi funding, Senegal would have seen a similar zero difference in the measles coverage rate relative to the BCG coverage rate, we conclude that 3.8 percentage points is the correct estimate for Gavi's effect. Heuristically, one can think of our identification strategy as averaging many of these mini natural experiments across time and countries to determine the effect of Gavi's programs.

Using this approach, we estimate a 3-percentage-point increase in coverage across all Gavi-funded vaccines, but the impacts are substantial larger, ranging from 10 to 20-percentage points, for two new vaccines, pneumococcal and rotavirus, that were mostly not present in these countries prior to Gavi's support.[4] An event-study specification provides precise estimates of the increase in coverage with no evidence of pre-existing differential trends, supporting our identifying assumption. We also document that coverage of non-Gavi funded vaccines was rising around the same time, suggesting that the focus on Gavi-funded vaccines was not crowding out efforts to distribute other vaccines.

Using a similar strategy, we estimate the impact of the Gavi-funded introduction of a vaccine on mortality from related causes between the ages of 1 and 59 months (we omit neonatal mortality since, except for the hepatitis B birth dose, infants do not receive vaccinations at birth), which we hereafter refer to as child mortality. We compare trends in child mortality from causes related to

[4] Gavi originally supported vaccines already available in low-income countries, such as vaccines for measles and rubella, diphtheria, pertussis and tetanus (DPT), and hepatitis B (HepB). Beginning in 2008, they began funding pneumococcal and rotavirus vaccines.

Gavi-funded vaccines to trends in child mortality from other causes. We use a flexible specification with country X cause of death, country X year, and cause of death X year fixed effects to allow for identification of these mortality effects. We find that child mortality from causes related to Gavi-funded vaccines falls by 0.5-2 children per 1000 live births for each vaccine introduced. These improvements in child survival appear driven by reductions in respiratory deaths and diarrheal deaths, both likely affected by the new vaccines Gavi supports. Specifically, the pneumococcal vaccine protects against respiratory infections, while diarrhea resulting in severe dehydration is a common complication of rotavirus. As with coverage, we find no evidence of increases in child mortality from unrelated causes which might have suggested crowd-out of resources for other illnesses.

Using these estimates of Gavi's impact on child mortality, we conclude that foreign aid through Gavi saved between 825,000 and 3.3 million lives between 2000 and 2019 and estimate the cost of doing so between US $3,940 to US $15,757 per life saved. Using data on life expectancy at age 5 and a conservative estimate for the value of a statistical life, we find a lower bound estimate of the economic benefit of Gavi's aid equal to US$76 billion. This number is more than five times Gavi's total investment of US$13 billion. However, we also show that the benefits are potentially an order of magnitude larger. In this paper, we focus only on one benefit of vaccination: reduced child mortality. Some of the vaccines Gavi funds target older ages (e.g., HPV) and have longer-term impacts on health. Gavi's support for strengthening health systems may have more far-reaching benefits as well. Thus, these estimates should be considered a lower-bound on the full impact of Gavi on welfare.

Our paper is not the first to examine the effect of Gavi. Two early evaluations document positive effects of Gavi funding (Lu et al, 2006; Hulls et al, 2010), but rely on system GMM estimation for identification, raising concerns about endogeneity, and use older data on fewer recipient countries and fewer funded vaccines. In more recent work, Jaupart et al. (2019) find positive effects of Gavi using an event study methodology. However, they consider only one event, the founding of Gavi, and compare countries eligible for Gavi funding to countries not eligible for Gavi funding based on GNI per capita. Accordingly, they are unable to exploit the differential timing of Gavi funding across countries, time, and vaccines which is key to our identification strategy. They estimate unexpectedly large reductions in infant and under-five mortality (over 12 deaths per 1,000 live

births), which are possibly driven by differential pre-trends between Gavi-eligible and Gavi-ineligible countries. Concurrently, Dykstra et al. (2019) argue that most Gavi aid just replaced money already spent on vaccination using a regression discontinuity design that exploits the GNI per capita eligibility threshold. While their paper is well identified, their results are applicable only to countries near the eligibility cutoff (the least poor of the low-income countries) and are not applicable to newer vaccines like pneumococcal or rotavirus (where they argue the eligibility cutoff was not strictly enforced). Given that pneumonia and diarrheal diseases are a significant cause of mortality among children in poor countries, examining the impact of these vaccines is essential to understanding the full impact of Gavi.

Additionally, our paper is an important contribution to the debate on the effectiveness of foreign aid. A large, early, literature documented positive impacts of foreign aid, but an equally noteworthy literature disputed the positive impact. For example, Hansen and Tarp (2000) find a positive link between foreign aid and economic growth; in a subsequent paper, Hansen and Tarp (2001) argue foreign aid promotes growth through increased investment. Other research is supportive of the idea that foreign aid has a positive effect on economic growth under the correct conditions. Two prominent examples are Burnside and Dollar (2000) as discussed above and Dalgaard et al. (2004) that demonstrates the role climate can have in promoting a positive impact of aid on growth. At the same time, other prominent papers argue that some of these results are sensitive to how these studies define aid, and how they choose the countries and years included in the sample (e.g., Easterly et al., 2004; Roodman, 2007).

One critique of the foreign aid literature is the need for careful consideration of the causal impact of aid. Many well-identified studies fail to find beneficial effects (Rajan and Subramanian, 2008; Werker et al., 2009) and sometimes even find harmful effects (Nunn and Qian, 2014; Crost et al., 2014). Still, other recent papers that pay careful attention to timing as well as identification find a positive, if sometimes modest, overall effect on economic growth (Clemens et al., 2011; Galiani et al. 2017).

A key take-away from the uncertainty in this literature is that rigorous evaluation of aid programs is needed to ensure aid dollars are not wasted. Qian (2015) also recommends a shift towards the study of specific forms of aid, since the heterogeneous types of aid that make up aggregate aid are likely to impact different development outcomes and over different time periods. Our paper

contributes to this literature by carefully documenting the causal impact of a foreign aid program with a close link between aid and outcomes, namely the impact of Gavi aid dollars on vaccine coverage and child health.

The paper proceeds are follows. Section II provides background on Gavi, while Section III presents our empirical strategy. Section IV describes the data we use on Gavi funding, vaccine coverage, and cause-specific child mortality rates. Section V presents our results and Section VI concludes.

II Background on Gavi

Gavi, the Vaccine Alliance was created in 1999 by its core partners the Bill and Melinda Gates Foundation, the World Health Organization, UNICEF, and the World Bank. While the Gates Foundation provided initial funding for the alliance, sovereign donors promptly provided additional support. The United Kingdom was the first country to provide funding to the alliance in 2000, followed quickly by Denmark, Norway, Sweden, the Netherlands, and the United States and later joined by Canada, Ireland, France, and Luxembourg. By 2005 the alliance had US$1.67 billion in donations, about half of which came from sovereign countries (Chee et. al, 2008). The aim of the partnership was to increase uptake of vaccines particularly in developing countries. Importantly, the alliance hoped to accomplish this goal despite the inability of a predecessor organization, the Children's Vaccine Initiative (CVI), that failed to make significant progress on increasing global immunization because of insurmountable disagreements among its various partners.

At the first meeting of the alliance, the board decided to limit Gavi support to only the lowest income countries, defined as those with World Bank measured per-capita incomes at or below US$1,000 (GNI as of 1998). At the time, this rule made 74 countries eligible to apply for Gavi support, but soon four countries (Albania, Bosnia and Herzegovina, China, and Turkmenistan) exceeded the threshold and were no longer eligible (Kallenberg et al., 2016). Subsequently, Gavi has revised upward the eligibility threshold which, as of 2019, stands at US$1,580.[5]

An important goal of Gavi is sustainable vaccination finance. The alliance aims for countries to continue their vaccination programs even after they are no longer receiving funding from Gavi. To

[5] https://www.Gavi.org/types-support/sustainability/eligibility

accomplish this goal, Gavi uses a tiered co-financing policy described in Kallenberg et al. (2016). Initially, low-income countries contribute US$0.20 per dose and Gavi funding covers the remaining cost. The countries continue to pay this cost until their per-capita income exceeds the World Bank low-income country threshold (US$1035 as of 2019). Once a country's income surpasses this level, their co-financing requirement increases 15% per year until their per-capita income surpasses the current Gavi eligibility threshold. At that point, their co-financing requirement increases linearly to 100% over a period of 5 years. While a country no longer receives Gavi funding post-graduation, it is eligible to purchase vaccines through UNICEF at Gavi prices which in some cases are substantially lower than what they could obtain on the open market.

As explained in Dykstra et al (2019) it is useful to categorize Gavi funded vaccines into two broad categories. The first group of vaccines are long-standing, inexpensive vaccines that were commonly found in developing countries prior to the founding of Gavi. These vaccines include the diphtheria, pertussis and tetanus (DPT) and hepatitis B (HepB) vaccines. Prices for these vaccines range from US$0.10 to 0.6.[6] Gavi has also modernized the vaccine programs of recipient countries. For example, it has replaced the DPT vaccine with the pentavalent vaccine which protects against DPT, HepB and Haemophilus influenzae type b (Hib). The pentavalent vaccine prices have ranged from US$3.6 in 2004 to a low of US$1.2 in 2020.

The second group of vaccines are newer vaccines which were primarily unavailable or present in only a small number of low-income countries prior to Gavi funding these vaccines beginning in 2008 (rotavirus and pneumococcal). When launched, the rotavirus vaccine cost US$5.00 per dose and the pneumococcal vaccine cost US$7 per dose. Gavi procured and purchased the pneumococcal vaccine via an innovative advanced market commitment described by Kremer et al. (2020). Overall, Gavi has spent over US$13 billion on country programs since its founding.[7]

Most of the money Gavi has distributed since 2000 ($10 out of the $13 billion) has gone to actual purchasing of vaccine doses. However, Gavi does provide support for vaccine delivery systems. Vaccine introduction includes one-off costs for training, planning, social mobilization, and a communication campaign for example. In addition, while most of Gavi funding supports routine

[6] UNICEF vaccine procurement pricing data are available at: https://www.unicef.org/supply/pricing-data.
[7] https://www.Gavi.org/sites/default/files/publications/progress-reports/Gavi-Progress-Report-2018.pdf

immunization for infants, Gavi does also provide funding for catch-up campaigns that target older children (measle and rubella, for example) and even adults (meningococcal meningitis and yellow fever, for example).

III Empirical Strategy

Our empirical strategy relies on variation in Gavi support across countries, time, and vaccines. We estimate a difference-in-difference-difference with a complete set of fixed effects. Specifically, we include country X vaccine, country X cohort, and vaccine X cohort fixed effects (subsuming country, vaccine, and cohort fixed effects) in all our regressions. We estimate:

$$Y_{ivdt} = \beta_1 Post_{ivt} + \theta_{iv} + \theta_{it} + \theta_{vt} + \varepsilon_{ivdt} \quad (1)$$

where Y_{ivdt} is coverage of dose d of vaccine v in country i for the cohort born in year t and $Post_{ivt}$ is a dummy variable indicating that the cohort was born after Gavi had provided funding for the introduction of vaccine v in country i. We cluster our standard errors by country.

The two-way interacted fixed effects eliminate bias from many possible sources. The country X vaccine fixed effects eliminate bias from potentially endogenous decisions to fund certain vaccines in certain countries. The country X cohort fixed effects ensure that we are relying only on variation across vaccines, comparing those that were or were not funded by Gavi in a particular country in a particular year. These fixed effects absorb all time-varying differences across countries that might drive changes in vaccine coverage. Finally, the vaccine X cohort fixed effects eliminate bias from global time-varying differences across vaccines, such as global supply changes or, for our mortality estimates, global trends in mortality from certain causes.

Due to the inclusion of these fixed effects, the only remaining bias will arise from time-varying country-specific differences in coverage for specific vaccines. If vaccine coverage for vaccines Gavi will fund in the future in a particular country is trending differentially than other vaccines in that same country, relative to differences in trends between these same vaccines in non-Gavi-funded countries, this would signal a problem for our strategy. We examine possible pre-existing trends with an event-study specification. This specification has the added benefit of allowing the impact of the Gavi-funded introduction of a vaccine to vary flexibly over time. We estimate:

$$Y_{ivdt} = \sum_{l=-\mathrm{T}+1}^{\mathrm{T}} \beta_l D_{ivt}^{l} + \theta_{iv} + \theta_{it} + \theta_{vt} + \varepsilon_{ivdt} \quad (2)$$

where D_{ivt}^{l} indicates that the cohort born in year t in country i was born l years after (or before if l is negative) vaccine v was introduced. Estimates of β_l for $l \geq 0$ tell us the impact of Gavi on coverage for cohorts born the year the vaccine was introduced and later, while estimates of β_l for $l < 0$ tell us whether coverage for this vaccine relative to other vaccines, was trending differently, in the adopting countries relative to the non-adopting countries, before Gavi funding was introduced. Our data on vaccine coverage spans many years before and after the introduction of the Gavi-funded vaccines; therefore, we are able to estimate impacts using a 20-year window centered around the vaccine introduction.

Our empirical specifications when studying child mortality from related, vaccine preventable, causes of death are similar, but complicated by the fact that multiple vaccines can affect some causes of death, limiting the within-country variation in relevant Gavi funding. Therefore, we link vaccines to causes of death in two ways. First, we exploit as much within-country variation as possible, by linking each Gavi-funded vaccine to the primary cause of death it targets. We estimate:

$$Y_{ict} = \beta_1 Post_{ict} + \theta_{ic} + \theta_{it} + \theta_{ct} + \varepsilon_{ict} \quad (3)$$

$$Y_{ict} = \sum_{l=-\mathrm{T}+1}^{\mathrm{T}} \beta_l D_{ict}^{l} + \theta_{ic} + \theta_{it} + \theta_{ct} + \varepsilon_{ict} \quad (4)$$

where Y_{ict} is the number of deaths among children under the age of 5 per 1000 live births (excluding deaths among infants less than 1 month) in country i, year t, from cause of death c, $Post_{ict}$ is a dummy variable indicating that Gavi has provided funding to country i, prior to year t, for a vaccine primarily affecting deaths from cause c, and D_{ict}^{l} indicates that Gavi introduced funding for such a vaccine exactly l years before t (or after t if l is negative). We include the full set of interacted fixed effects to ensure our results are not driven by country-specific differences over time, country-specific differences across causes of death or global time-specific differences across causes of death. Alternatively, we allow each vaccine to impact every medically related cause of death by estimating:

$$Y_{ict} = \beta_1 NumVaccines_{ict} + \theta_{ic} + \theta_{it} + \theta_{ct} + \varepsilon_{ict} \quad (5)$$

where $NumVaccines_{ict}$ is the number of vaccines Gavi has funded in country i, prior to year t, that can impact cause of death c. We discuss the connections between vaccines and causes of death in section IV.C..

In specifications (3) and (5), we estimate the immediate impact of Gavi funding on child mortality even though not all children under 5 will be vaccinated immediately, as most Gavi funding focuses on routine immunization of infants. We expect the short run effect of vaccine introduction on child mortality to be smaller than the long run effect as it will take years for all children under 5 to be vaccinated. The β_1 coefficient in specifications (3) and (5) will average these short run and long run effects. However, the event study specification will allow us to separately estimate the short run and long run effects.[8]

IV Data

IV.A. Gavi funding

From Gavi, we obtained a list of launch dates for Gavi funding for each supported vaccine in each country. When multiple launch dates were listed, we used the earliest date to minimize concerns about endogeneity.[9] We also obtained, from Gavi's website, data on the amount of funds approved to be disbursed to each country each year under various sub-categories. Some sub-categories indicate the vaccine for which the money is approved, while some sub-categories are broader (such as "Health Systems Strengthening"). We define the first year Gavi funded a vaccine as the first year money is approved for a vaccine-specific line item.[10] We primarily use the launch dates but find similar results using the funding data.

Table 1 presents the number of countries that introduced a particular vaccine in each year using the launch dates. From the table we can see that each vaccine was introduced in countries around the world in a staggered manner and that the timeline differs for each vaccine (e.g., both the pneumococcal and rotavirus vaccines are first introduced around 2008-2009 but the pneumococcal

[8] Most of Gavi's support funds routine immunization of infants, but Gavi occasionally funds catch-up campaigns (for measles-rubella, for example) for which older children are eligible. Theoretically, our child mortality results will include the impact of such campaigns since we examine child mortality not infant mortality, but our coverage estimates would be biased towards zero because our control cohorts, born before Gavi introduced funding, would be partially treated. In practice, measles, rubella, and polio catch-up campaigns are unlikely to affect our results since funds were not specifically allocated for these campaigns until 2016 the last year for which we have coverage data. Funding for meningitis A campaigns began in 2011 but we do not have coverage data for meningitis and campaigns for yellow fever began in 2013, but yellow fever coverage accounts for very few of our observations.

[9] Multiple launch dates often coincide with funding for follow-up campaigns to help vaccinate older children.

[10] Discrepancies for the first year of Gavi support across these two data sources are primarily due to the launch date being 1 year before or after the first year of funding. Allowing for these discrepancies, the launch dates and the first year of funding match for 92% of country-vaccine pairs.

vaccine was introduced in more countries and on average earlier). Some vaccines were more targeted (Gavi launched the Japanese encephalitis vaccine in only 5 countries), while others were distributed more broadly. Appendix Table A1 presents this information using the first year a country received funding in a vaccine-specific sub-category.

This staggered introduction results in substantial within-country variation in when each vaccine is launched with Gavi support which we exploit for identification. For example, Angola introduced the pentavalent vaccine with Gavi funding in 2006, but did not introduce the pneumococcal vaccine until 2013, the rotavirus vaccine until 2014, and the measles-rubella vaccine until 2018.

The factors that lead countries to adopt certain vaccines (with or without Gavi support) at certain times are varied. Burchett et al. (2012) stress the importance of funding availability, political will to promote vaccines, and the local disease burden of the various pathogens. Similarly, Makinen et al. (2012) argue that countries are influenced by WHO recommendations, the availability of country-specific data on the burden of disease, and the overall affordability of the vaccine.

In the context of Gavi-supported introduction, we identified several factors that have driven vaccine adoption: pricing and sustainability concerns, local vaccine infrastructure, specific Gavi recommendations and policies, the availability of local burden of disease estimates, WHO recommendations, and vaccine supply constraints. For example, according to Gavi (2016), the roll out of the rotavirus vaccine did not meet initial Gavi coverage targets by 2015 due to affordability concerns. Affordability is a major factor, as countries are typically committing to perennial purchases of the vaccine, as removing vaccines from a national immunization program is a rare occurrence, and discounted vaccine prices are guaranteed only for a limited number of years. The same report also notes that concern about cold chain quality also slowed uptake.

Similarly, Gavi policy required pentavalent coverage above 70% to apply for some new vaccine support but did not apply this threshold to the Japanese encephalitis and meningitis A vaccines. When the pneumococcal vaccine was introduced, countries had to have achieved 70% or higher coverage of DTP to apply for Gavi support (Gavi, 2018). Gavi also discouraged some countries from applying for new pentavalent support due to an expected global shortage of the vaccine (Chee et al, 2008). The availability of a burden of disease report to make the case that vaccine purchase is cost effective, is an additional factor that drives adoption. Initially, Gavi recommended a burden of disease study before a country applied for Hib support, for example (Chee et al, 2008) and the

WHO did not initially recommend rotavirus vaccine outside of the Americas and Europe because of the absence of such a study (WHO, 2007).

WHO recommendations through its Strategic Advisory Group of Exports (SAGE) also influence take up. For example, a 2014 recommendation to improve coverage of the meningococcal A vaccine was followed by increased vaccine adoption in the meningitis belt, which stretches from Senegal to Ethiopia in sub-Saharan Africa (WHO, 2019). There is regional variation as well in WHO recommendations. In 2013, 11 member states of the South East Asian Region of the WHO endorsed a resolution to promote rubella vaccine. Subsequently, Bangladesh, India, Myanmar and Indonesia introduced the measles/rubella vaccine (WHO, 2013). Finally, our personal correspondence with Gavi indicated that distribution of both the pentavalent and pneumococcal vaccines was significantly constrained by manufactured supply capacity, leading to a staggered roll out of the vaccine across countries.

IV.B. Vaccine coverage data

We obtained data on vaccine coverage across countries, vaccines, and cohorts from the World Health Organization and UNICEF WUENIC working group. The WHO provides survey estimates of vaccine coverage and WHO official estimates that combine data from administrative sources and survey sources.[11] Due to concerns about accuracy of the administrative data underpinning the official estimates amid incentives to inflate official estimates, we prefer the survey data for our main estimates but show our results are robust to using the official estimates.[12]

The WHO collected data from more than 881 surveys across 152 countries to calculate coverage rates of various vaccines for different cohorts. For example, the data includes coverage estimates for 16 different vaccine doses (separating out multiple doses of some vaccines) for the cohort born in 2012 in Ghana as reported in the Ghana Demographic and Health Survey in 2014. Data for the U.S., another example, comes from the National Immunization Surveys from 2002 to 2014. Some data is based on immunization cards viewed by enumerators while some is reported by household

[11] The WHO official estimates are taken from administrative data with some editing to account for the possibility of inaccurate data. For example, the WHO official estimates replace administrative data if coverage rates calculated from survey data strongly indicate discrepancies. The WHO official estimates impute values for missing data using linear interpolation. Other corrections are made to reconcile inconsistencies between dose numbers.

[12] Gavi creates one incentive to inflate official estimates since the introduction of new vaccines is predicated on reaching a coverage threshold for DTP, as described above.

members. Some surveys report coverage estimates for multiple cohorts, but most focus on the most recently born cohort.[13]

Table 2 reports summary statistics from this data on 12 different vaccines from 1985 to 2014. Since surveys are conducted at varying intervals and usually only collect data on coverage for recently born cohorts, there are many missing observations. On average, we have coverage rates of any vaccine for 8 cohorts per country, and for each country-cohort that we have data, we have coverage rates for 7 vaccines (counting each dose separately). For most vaccines, we see increases in coverage over time, but these are likely to underestimate the true growth since, given the incompleteness of the data, the sample is skewed towards more developed countries earlier in the time period.

IV.C. Child mortality data

We obtained data on child mortality rates from specific causes via the World Health Organization's Global Health Observatory (GHO). The GHO provides data on the number of deaths per 1000 live births from groups of causes for each year from 2000 to 2017 and for almost 200 countries. The data is separated into deaths among 0-27-day-old infants and children between 1-59 months of age. We focus on 1-59-month mortality (hereafter, *child mortality*, for brevity), since infants are not generally vaccinated in the first month of life; in fact, in additional results, we show that the impact on mortality for 0-27-day-old infants is negligible. Our results are also robust to using all under-5 deaths.

Table 3 lists 12 causes of death and provides means from 2000, 2005, 2010, and 2015.[14] Mortality rates have generally fallen over time for almost all causes, but they vary substantially across causes as do the rates of decline. For example, acute lower respiratory infections accounted for the highest number of child deaths at almost 8 per 1000 live births in 2000, and the rate has fallen by 50%

[13] One caveat when using survey data is that the immunization status of children who have died is not recorded (McGovern and Canning 2015). Our reliance on within-country, cross vaccine variation, helps us with this problem. In order to bias our results, the differential coverage rate for a funded vaccine relative to an unfunded vaccine would have to differ for children who died relative to children who survived. Specifically, in order to negate our result, children who died would have to be *less* likely to receive the Gavi-funded vaccines relative to other vaccines, relative to children who survived. This seems unlikely, but we also note that the WHO's official estimates which are primarily based on administrative data collected from service providers give us similar results.

[14] The GHO provides data on 13 groups of causes but no deaths are attributed to 1 cause ("Sepsis and other infectious conditions of the newborn") for children aged 1-59 months; we include data on that cause only when including neonatal mortality in our estimates.

from 2000 to 2015. Birth asphyxia and trauma accounted for the lowest number of deaths at 0.5 per 1000 live births in 2000, and the rate has fallen by 27% from 2000 to 2015.

As discussed above in section III, we assign the vaccines that Gavi funds to these causes of death in multiple ways since some vaccines can prevent deaths attributed to multiple causes. These linkages are based on the World Health Organization's Immunization in practice: A practical guide for health staff (2015) and consultation with a public health expert, Richard A. Cash, M.D., M.P.H. and Senior Lecturer at the Harvard T.H. Chan School of Public Health. When estimating specifications (3) and (4), we maximize the within-country, across cause-of-death variation by focusing on the cause of death most closely linked to each vaccine. These are indicated in Column (5) of Table 3. Specifically, the measles, meningitis and Japanese encephalitis vaccines are linked to their eponymous causes of death, the rotavirus vaccine is linked to diarrheal deaths, and the pneumococcal and pentavalent vaccines are linked to respiratory deaths. On the other hand, specification (5) allows vaccines to affect multiple causes of death. Some diseases, such as measles, can compromise immunity; the measles vaccine could reduce the number of child deaths attributed to diarrheal diseases or respiratory infections. In addition, the pneumococcal and pentavalent vaccine can prevent diseases that, in some rare cases, lead to meningitis. Column (6) indicates the vaccine-cause of death linkages we use to calculate the number of vaccines Gavi has introduced that could affect each cause of death. Specification (5) is, in some ways, more complete, allowing all vaccines to affect the causes of death that might result from the disease prevented. However, meningitis is a very rare consequence of the pneumococcal disease, for example, and it is unrealistic to expect the pneumococcal vaccine to affect meningitis deaths as much as it affects pneumonia deaths. Hence, while we estimate both specifications (3) and (5), we prefer specification (3). If the measles vaccine, for example, also reduces deaths from other causes, that would only bias our estimates from specification (3) towards zero since we are comparing measles deaths to other deaths after Gavi-funding of the measles vaccine. Focusing on the most affected cause of death in specification (3) also allows us to estimate the event study, specification (4).

Our empirical strategy relies on data on mortality by cause; errors in attribution of deaths to specific causes could bias our results. We argue that such errors are unlikely to be related to Gavi funding for a related vaccine and therefore, would simply lead to attenuation bias. Nevertheless, we show below that our results are robust to alternate specifications that do not rely as much on

cause of death attribution by comparing the effect of vaccine introduction on all vaccine preventable causes of death relative to all other causes.

V Results

V.A. Impact of Gavi-funding on vaccine coverage

Table 4 presents estimates of specification (1) using the WHO-compiled survey data on vaccine coverage. Panel A estimates the regression with data on all countries in the dataset, while Panel B includes countries that have received Gavi funding for the introduction of any vaccine (hereafter "Gavi-recipient countries") and countries with slightly higher GNI per capita in 2000 (up to $3500 in 2010 dollars).[15] All specifications include country X vaccine, country X cohort, and vaccine X cohort fixed effects. Columns (1) to (3) determine the first year of Gavi support from the launch dates, while Columns (4) to (6) use the vaccine-specific line items from the approved funds. Columns (1) and (4) include coverage data from all vaccines. Columns (2) and (5) examine Gavi-funding of previously available vaccines by excluding observations on coverage of the pneumococcal and rotavirus vaccines after they are launched in a particular country (to be clear, observations on coverage of any vaccine before it is funded in a particular country are included as the comparison). Columns (3) and (6) focus on Gavi-funding of these new vaccines (pneumococcal and rotavirus), dropping observations on the previously available vaccines in the analogous way.

We see a significant 2-3 percentage point increase in coverage after a vaccine is introduced with Gavi assistance (Column 1). This muted result may be expected given the high existing coverage rates of some of these vaccines prior to the availability of Gavi funding. Along these lines, we see a much larger impact for the newly available vaccines (Column 3) than vaccines which had pre-existing distribution (Column 2). The coverage rates for pneumococcal and rotavirus increased by 10-20 percentage points depending on the choice of control countries.

[15] Gavi eligibility is based on GNI per capita in 1998, however we use GNI per-capita in 2000 because it is available for a larger number of countries. Even still, GNI per-capita in 2000 is not available for all countries. All Gavi-eligible countries with data in 2000 had GNI per capita of less than $1860 (in 2010 $) except for Cuba which had GNI per capita of $3411 (Cuba received Gavi eligibility because of the lack of reliable data on Cuban GDP in 2000). The $3500 cut-off adds 17 countries that never received Gavi funding. Our results are not sensitive to this cut-off, but we limit our statistical power if we restrict our analysis to only those countries that have ever received Gavi funding.

Appendix Table A2 replicates this table using the WHO official estimates of coverages, which are based on administrative data but revised when the WHO has reason to believe the administrative data is inaccurate.[16] The results are more precisely estimated, statistically significant at the 1% level for many estimates. Strikingly, the estimates of the impact for newly available vaccines are almost twice as big as our previous estimates, but the estimates of the impact for previously available vaccines are slightly smaller. One possible explanation is that Gavi requires countries improve their coverage data accuracy in order to continue receiving funding. Since there is more data on coverage of previously available vaccines before receipt of Gavi funding, this would bias the impact downwards for those vaccines more than for newly available vaccines if pre-Gavi funding coverage rates are inflated.

As discussed above, the full set of two-way interacted fixed effects account for a host of possible omitted variables. The identifying assumption is that coverage of Gavi-funded vaccines would have trended similarly to coverage of non-Gavi funded vaccines, in adopting and non-adopting countries, in the absence of any Gavi-funding. To provide support for this assumption, we look for differences in trends between these vaccines prior to the Gavi-funded introduction with our event-study specification (2). Figure 1 plots the conditional difference in coverage between Gavi-funded vaccines and other vaccines for each time period (relative to this difference from 10 or more years prior to the introduction). Effects are plotted along with their 95% confidence intervals. Importantly, these effects cannot be driven by time trends or country-specific effects as we include cohort-specific country fixed effects.

Figure 1 supports our identifying assumption: it does not appear that coverage of these particular vaccines was trending differentially prior to Gavi introduction – an F-test of all pre-introduction coefficients fails to reject the null hypothesis of no differences ($p=0.49$). We also see a marked increase in coverage soon after Gavi funded a vaccine, beginning in year 2. An F-test of all post introduction coefficients rejects the hypothesis of no effect ($p<0.01$).

One benefit of the event study specification is that it allows flexibility in the impact over time; we see that the increase in coverage rates occurs in year 2 and remains consistent over the next 8 or

[16] In Appendix Table A2, we are able to estimate specification (1) using observations for only new vaccines and only previously available vaccines since we have more observations on coverage for the new vaccines. The survey data is more limited, requiring that we continue to use the other vaccines in the comparison group in Table 1.

more years. A likely explanation for the lag in the impact on coverage is that the launch dates are announcement events and that vaccine distribution ramps up after that. Especially in large countries, Gavi's strategy based on WHO guidance is to stagger distribution and ramp up over a few years instead of aim to distribute nation-wide in the first year. Also contributing to this lag might be the fact that in the first year of Gavi-funded vaccine distribution, there are usually two cohorts being targeted: children born in the previous 12 months and newborns and vaccines may not be available to vaccinate both cohorts fully.

Appendix Table A3 presents several robustness checks. We get very similar results when we exclude coverage estimates of the oral polio vaccine and the hepatitis B birth dose both of which are not supported by Gavi (Columns 1 and 6). Our primary specification includes them since the inactive polio vaccine and the pentavalent vaccine are supported by Gavi and cover the same diseases (respectively) and survey data may combine coverage rates for these two vaccines in a catch all polio category or hepatitis B category. Columns (2) and (7) exclude estimates of measles and rubella coverage to ensure that any correlations between efforts by Gavi and the Measles & Rubella Initiative, which also supports vaccination programs, are not driving our results.[17] Our results are also robust to including country X vaccine linear trends (Columns 3 and 8) in addition to our complete set of two-way fixed effects. Finally, we include region X vaccine X cohort fixed effects; our results are similar and often statistically significant, particularly when we define the regions more broadly (splitting up Africa and Asia into 2 regions instead of 3).[18] These fixed effects would account for any regional pushes towards eradicating certain diseases that might be correlated with Gavi funding.

V.B. Impact of Gavi funding on non-funded vaccines

Our identification exploits country X cohort fixed effects which control flexibly for all time-varying differences across countries that might drive changes in vaccine coverage, as long as they impact all vaccines in the same way. Note that, like many analyses of foreign aid or government

[17] Between 2001 and 2019, the Measles & Rubella Initiative has spent more than US$1.2 billion supporting measles vaccination in 88 countries. Since we find similar results excluding the measles and rubella coverage results, we conclude the Initiative's activities are not driving our results. It is also worth noting that Gavi is one of the Initiative's key supporters. https://measlesrubellainitiative.org/learn/about-us/

[18] The regions used in Columns (5) and (10) are the WHO regions. We combine some of these regions together in Columns (4) and (9).

policies, our approach is vulnerable to bias from substitution across outcomes. Since Gavi requires cost-sharing, governments may choose to substitute money away from vaccines they were already supporting towards vaccines Gavi is helping them introduce. If this were the case, the increase in vaccine coverage after introduction could be driven as much by reductions in coverage of other vaccines as by increases in coverage of Gavi-funded vaccines. We address this possibility by estimating the impact of the introduction of a country's first Gavi-funded vaccine on coverage of vaccines that have not (yet) been introduced by Gavi in that particular country. If our previous results were driven by substitution across vaccines, we would expect to see a negative impact of Gavi funding any vaccine on coverage for other vaccines.

Columns (1) and (3) of Table 5 estimate the change in vaccine coverage when Gavi first introduces any vaccine (not including the introduced vaccine itself), first using launch dates and then the approvals and disbursements data to determine the first year of funding. Columns (2) and (4) focus on bacilli Calmette-Guérin (BCG) vaccine coverage since this vaccine, for tuberculosis, has never been funded by Gavi. None of the estimates are statistically significant – in fact, five of the eight estimates are positive – demonstrating that increases in the coverage of Gavi-funded vaccines did not come at the expense of other non-Gavi-funded vaccines. Note that we cannot include country X cohort fixed effects in the regressions in Table 5 since doing so absorbs all variation in Gavi funding, but we do include country-specific trends.

Figure 2 plots event study estimates, similar to Figure 1, of the impact on coverage for vaccines that Gavi has not yet started funding, while Figure 3 plots an event study for the impact on coverage rates for the BCG vaccine. Year 0 is the first year any vaccine was introduced by Gavi in this country. Both figures confirm the results from Table 5, that, if anything, vaccine coverage of non-Gavi funded vaccines was increasing after the introduction of Gavi-funded vaccines. F-tests of all post-introduction coefficients reject the null hypothesis of no effect for BCG ($p = 0.024$) and for all vaccines ($p = 0.05$). Given that Gavi-funding of a particular vaccine was often paired with funding for other health care and vaccine delivery infrastructure, it is not surprising that coverage for these vaccines rose. In addition, any demand-side interventions to increase coverage may have led to children receiving multiple vaccines, including those not funded by Gavi. These marginal effects could also indicate that Gavi funding freed up funding for countries to support *non-Gavi-funded* vaccines but the results are not robust enough to make any such conclusions.

We emphasize that the positive trend in non-Gavi-funded vaccine coverage after Gavi introduction does not detract from our main result that Gavi funding improved vaccine coverage. This conclusion is again due to the country X cohort fixed effects in our preferred specification which flexibly control for the overall trends in a country's vaccine coverage. The improvements we estimated in Table 4 are in addition to these general improvements in vaccine coverage – leading them to possibly underestimate Gavi funding, if Gavi funding positively impacts this general trend. The results in Table 5 do suggest, however, that our main result is not simply crowd-out of other vaccines by Gavi-funded vaccines.

V.C. Impact of Gavi-funding on under-5 mortality from related causes

Increased vaccine coverage in low-income countries has long been a goal of global health policy making the estimated impacts on vaccine coverage notable; however, we are ultimately interested in the effects of increased vaccine coverage on welfare. To this end, Table 6 presents estimates from specification (3) on child mortality (per 1,000 live births) from vaccine preventable causes using the launch dates to determine the first year of Gavi-support. Panel A includes data from all countries, while Panel B only includes Gavi-recipient countries and other low-income countries. Column 1 uses all country-cause of death observations. Columns 2-5 present estimates which isolate the impact on deaths from specific vaccine preventable diseases: acute lower respiratory infections, diarrheal diseases, measles, and meningitis/encephalitis deaths. Specifically, for Columns 2-5, we use, as control observations, causes of death unaffected by vaccines and the other vaccine-affected causes of death before Gavi funded the relevant vaccines.

Recall from Table 2 that there is substantial variation in mortality rates across causes. Most likely, when estimating the effect of vaccine adoption, other vaccine-preventable causes of death are better counterfactual outcomes than causes of death unrelated to vaccines. Consequently, in column 6, we drop observations for all causes of death unrelated to any Gavi-funded vaccine, using just the temporal variation in when Gavi funded vaccines that affect these four causes of death. Column 6 provides our preferred specification.

Estimates from Table 6 indicate that launches of Gavi-funded vaccines reduce mortality from related causes by 1-3 children per 1,000 live births, depending on the cause of death we examine. Mirroring the results for newer vaccines in Table 4, impacts for respiratory deaths (affected by the new pneumococcal vaccine) and diarrheal deaths (affected by the new rotavirus vaccine) are larger

than for causes of death affected by pre-existing vaccines (measles, meningitis, encephalitis). Note, when we focus on each cause of death separately, the number of treated observations (observations after Gavi funded a related vaccine) falls. For example, the estimates for meningitis/encephalitis are estimated from only 85 treated observations as the vaccines that prevent these diseases are adopted by only a few countries.

The results are similar when using only low-income countries (Panel B) and when determining the first year of vaccine-specific funding from the disbursements data (Appendix Table A4). Appendix Table A5 offers additional robustness checks, such as linear country X cause of death trends and region X vaccine X cohort fixed effects, neither of which change our results. The results are also robust to using the natural log of child mortality (dropping the few zeros). We estimate the impact on total under-5 mortality, adding in deaths among infants 0-27 days old and find smaller but still statistically significant results. Finally, as a specification check, we estimate the effect of Gavi funding on deaths between 0 and 27 days, and find very small, statistically insignificant coefficients. This result is expected since newborns do not immediately receive vaccinations.

As discussed above, our strategy relies on cause of death data; errors in attribution could bias our results. While we believe noise in attribution would simply bias our estimates towards zero, we offer an alternative specification to address concerns about accurate attribution in Appendix Table A6. First, we collapse the cause-specific mortality data into deaths targeted by Gavi-funded vaccines (acute lower respiratory infections, diarrheal diseases, measles, and meningitis/encephalitis) and other deaths (such as injuries, malaria, etc.). Then, we estimate the impact of Gavi-support for any vaccine on child mortality, include country X year fixed effects to absorb the main effect, and estimate the additional effect of Gavi support on child mortality from vaccine-affected causes. The results are consistent with our findings in Table 6 – approximately 5-8 deaths from vaccine-affected causes are averted by the introduction of Gavi vaccine funding.[19] Figure 4 presents event study estimates from specification (4). Following Column 6 of Table 6, we include data from only the four causes of death affected by a Gavi-funded vaccine. As in all specifications, we control for country X cause of death, country X year, and cause of death X

[19] In the same table, we also look at the impact of Gavi-support for any vaccine on all-cause under-5 mortality from the World Development Indicators. We find consistent evidence of large decreases in under-5 mortality, but note that here we have to rely on country trends (instead of country X year fixed effects) to deal with possible differential trends across countries.

cohort fixed effects. The results indicate that Gavi-funding of a vaccine reduces mortality rates from related causes. The coefficients for post-introduction years are negative and statistically significant; the F-test of all coefficients after introduction of the vaccine rejects the null hypothesis of no effect ($p < 0.01$).[20] The biggest effect is estimated for five or more years after the introduction of a vaccine, perhaps not surprising because by that time all children considered in the child mortality rate would have been born after the vaccine was introduced. Supportive of our identification strategy, we see small, statistically insignificant conditional differences in mortality across causes of death that did and did not receive Gavi-funding in the years prior to the introduction of the vaccine; the p-value of the F-test of all pre-introduction coefficients is 0.30.

Table 7 presents estimates of specification (5), allowing each vaccine to affect any cause of death that could possibly be connected to the corresponding disease, as discussed above. The results are consistent with the results in Table 6: Gavi-funding for each additional vaccine reduces child mortality from related causes by around 1 child per thousand.[21]As with vaccine coverage, it is possible that reductions in child mortality from vaccine related causes may come at the expense of child deaths from other causes. This outcome could occur because health system resources are diverted towards these vaccines and their related illnesses and away from other diseases. If that were the case, our strategy of comparing deaths from related causes and deaths from unrelated causes may be, in part, driven by increases in deaths from unrelated causes. We explore this issue in Table 8, where we estimate the impact of any vaccine-specific Gavi support on mortality from causes of death unaffected by the funded vaccines (Columns 1 and 3) or causes of death which are

[20] Recall that Figure 1 suggested a 2-year lag between a vaccine launch and an impact on cohort-level coverage. Figure 4, on the other hand, suggests only a 1-year lag for the impact on child mortality. While this could be explained by catch-up campaigns that target older children, improving mortality rates immediately but also biasing the impact on coverage towards zero, or programs to improve vaccine infrastructure before vaccines are rolled out, it may also be due heterogeneous effects of vaccines on child mortality. Specifically, small initial coverage increases may have a substantial effect on mortality if those specific vaccines have a large effect on mortality. To investigate this possibility, Appendix Figure A1 re-estimates Figure 1 using only the vaccines related to causes of death in the GHO mortality data we use as the set of treated vaccines (rotavirus, measles, pneumococcal and HiB from the pentavalent vaccine – there is no coverage data for meningitis or encephalitis). Here, we see a more pronounced effect on coverage rates in year 1, although the coefficient is not statistically significant at conventional levels ($p = 0.105$).

[21] Since this specification focuses on variation in the number of funded vaccines that can affect each cause of death, isolating the impact on each cause of death, as we do in Columns (2)-(5) may not be well motivated since, the only post-funding observations included in Column (2) are among respiratory deaths suggesting that the most the independent variable can be is 1. This is mostly true, except for the fact that multiple vaccines can affect a given cause of death and be funded in the same year, resulting in the independent variable jumping from 0 to 3. We include Columns (2)-(5) primarily for completeness.

not affected by any of the Gavi-supported vaccines, such as injuries or malaria (Columns 2 and 4). Consistent with our results on vaccine coverage, we see a decline in child mortality from unrelated causes when Gavi introduces any vaccine, though the results are smaller than our main results in Table 7. One explanation for this result is that Gavi support frees up money for other health programs, but it could also indicate differential trends in mortality in Gavi eligible countries relative to non-Gavi eligible countries since these regressions can only include country-specific linear trends instead of country X year fixed effects. Our main estimates would not be biased by such differential trends as we compare mortality rates across causes of death; our estimates document declines in mortality relative to these trends. Regardless, we conclude that we find no evidence of crowd-out of other health funding that would affect child mortality.

V.D Cost-Benefit Analysis

While we have demonstrated that Gavi funding increased vaccine coverage and reduced child mortality by a substantial amount, the cost of the program, US $13 billion, is also substantial. A natural question to address is if the benefits of Gavi's programs outweigh the cost.

To answer this question, we first calculate lives saved from the Gavi program in country *i*, at year *t*, from vaccine *v* as follows:

$$Lives\ Saved_{i,t,v} = \frac{-\Delta mortality}{1{,}000} \times \frac{Birth\ Cohort_{i,t}}{1{,}000} \times Treated_{i,v,t}$$

Here $\frac{-\Delta mortality}{1{,}000}$ is our estimated reduction, from Table 6, in under 5 mortality per 1,000 live births caused by Gavi introducing funding for a specific vaccine (ranging from a conservative estimate of -0.5 to a high estimate of -2 deaths/1000 live births). $Birth\ Cohort_{i,t}$ is the size of country *i*'s birth cohort at time *t*. $Treated_{i,v,t}$ is a binary variable indicating that Gavi has introduced vaccine *v*, in country *i,* on or before time *t*.

To attach a monetary value to the number of lives saved we calculate:

$$Value_{i,v,t} = Lives\ Saved_{i,t,v} \times Life\ Expectency\ at\ 5_{i,t} \times VSLY_{i,t}$$

where $Life\ Expectency\ at\ 5_{i,t}$ is the life expectancy of a 5-year-old in country i at time t and $VSLY_{i,t}$ is the value of a statistical life year in country i and time t.[22] To estimate $VSLY_{i,t}$ we use per-capita income for country i at time t.[23] We use one times per-capita income as a conservative estimate and three times per-capita income as a high estimate. These estimates are consistent with the literature. For example, Jamison et. al. (2013) reviews the evidence on VSLY in low-income countries and conclude a reasonable estimate is 2-3 times per-capita income. Chang et al. (2017) argues that per-capita GDP should be a lower bound on VSLY which ranges from 1 to 3 times per-capita GDP.

To calculate the total benefits, we sum across all time periods, countries, and vaccine observations. We find that Gavi funding led to 825,000 lives saved, at a cost of $15,757 per life saved, using our most conservative mortality estimate, and 3.3 million lives saved, at a cost of US $3,940 per life saved using our highest mortality estimate. Our lowest estimate of the value of Gavi's program is US$76 billion (using our smallest mortality and VSLY estimates); our highest estimate is US$915 billion (using our largest mortality and VSLY estimates). Given that the overall budget for Gavi was US $13 billion this represents a return on investment of $5.85 to $70.38 per dollar spent.

VI Discussion and Conclusion

The role that foreign aid can have in improving well-being in low-income countries is one of the mostly hotly contested issues in economics. In this paper we argue that specific types of foreign aid can be both efficient and enormously beneficial to recipient countries.

We come to this conclusion by analyzing the impact that Gavi – an alliance aimed at expanding access to vaccines in low-income countries – has on the countries that receive its support. By exploiting the differential timing in Gavi support across countries and vaccines we estimate that Gavi's programs increased vaccine coverage rates 3 percentage points on average, with larger effects of over 10 percentage points for the newer vaccines, pneumococcal and rotavirus, that were

[22] Here we omit both discounting future benefits (as the life-years are gained in the future) and growth in GDP-per capita. Implicitly we are assuming that the discount rate and GDP-per capita growth rate are the same so these two effects exactly cancel.

[23] Data on life expectancy at age 5 and number of births are obtained from the United Nations, Department of Economic and Social Affairs, Population Division and are available at: https://population.un.org/wpp/. Data of per-capita GDP are obtained from the World Bank national accounts data and are available at: https://data.worldbank.org/. Data are adjusted to 2019 US dollars using the CPI.

primarily unavailable in developing countries prior to Gavi's founding. Additionally, we find that Gavi support has led to an average fall in under five mortality of 1-2 children per 1,000 live births. Importantly, this effect on mortality stems largely from reduction in respiratory deaths that are related to pneumococcal pneumonia and diarrhea deaths which are related to rotavirus infection. We estimate the narrow economic returns of these mortality gains to be at least $5.85 per $1 spent by Gavi. We view this as a lower bound on the return as our analysis does not estimate benefits such as vaccine-induced reduced morbidity, Gavi's health system strengthening support, and potential feedback from increased health to productivity.

The success of Gavi in channeling foreign aid into beneficial outcomes for recipient countries leaves many questions unanswered. Specifically, which attributes of Gavi are essential to its success? The focus on vaccination seems key, and one cannot help but wonder if there are other large-scale interventions with high probabilities of success in promoting desirable outcomes. The role of recipient country ownership, particularly in applying for and co-financing the interventions may be important as well. Finally, the unique public-private alliance structure of Gavi may explain, in part, why it succeeded where other global vaccination campaigns did not. We leave these compelling questions to future research.

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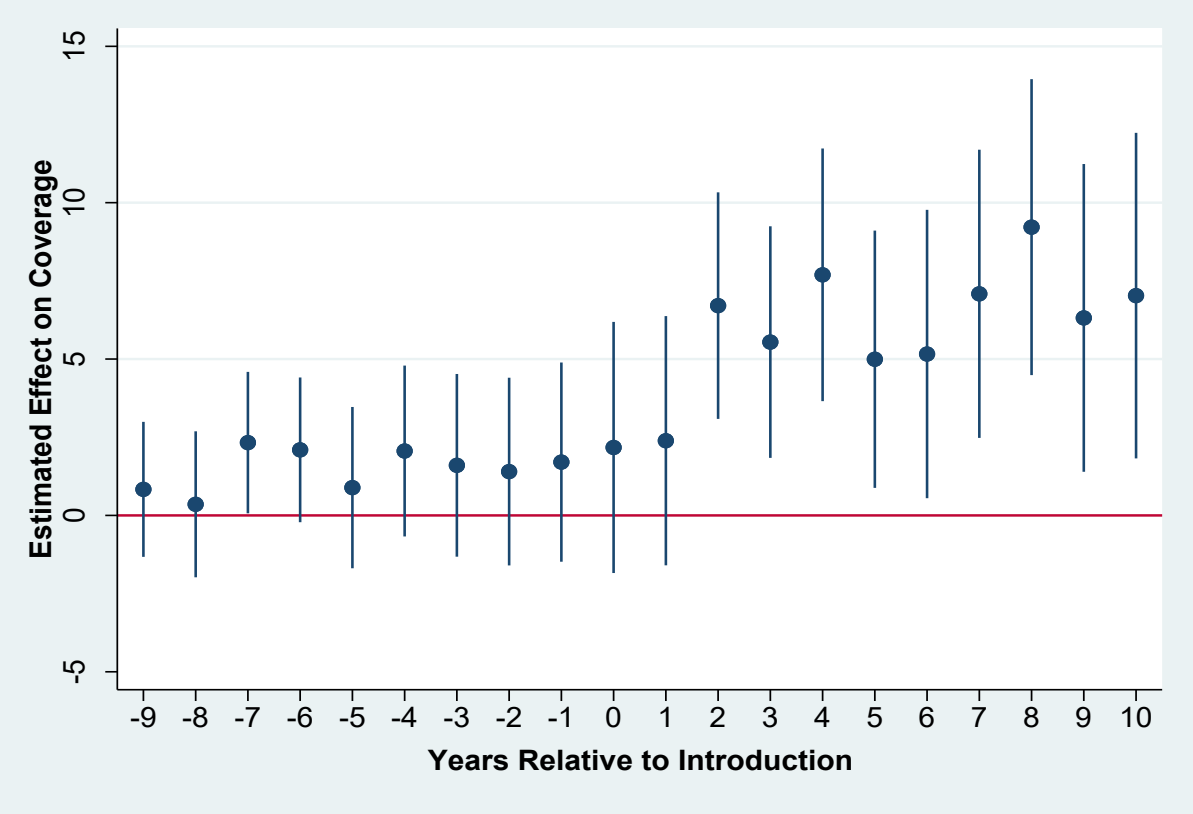
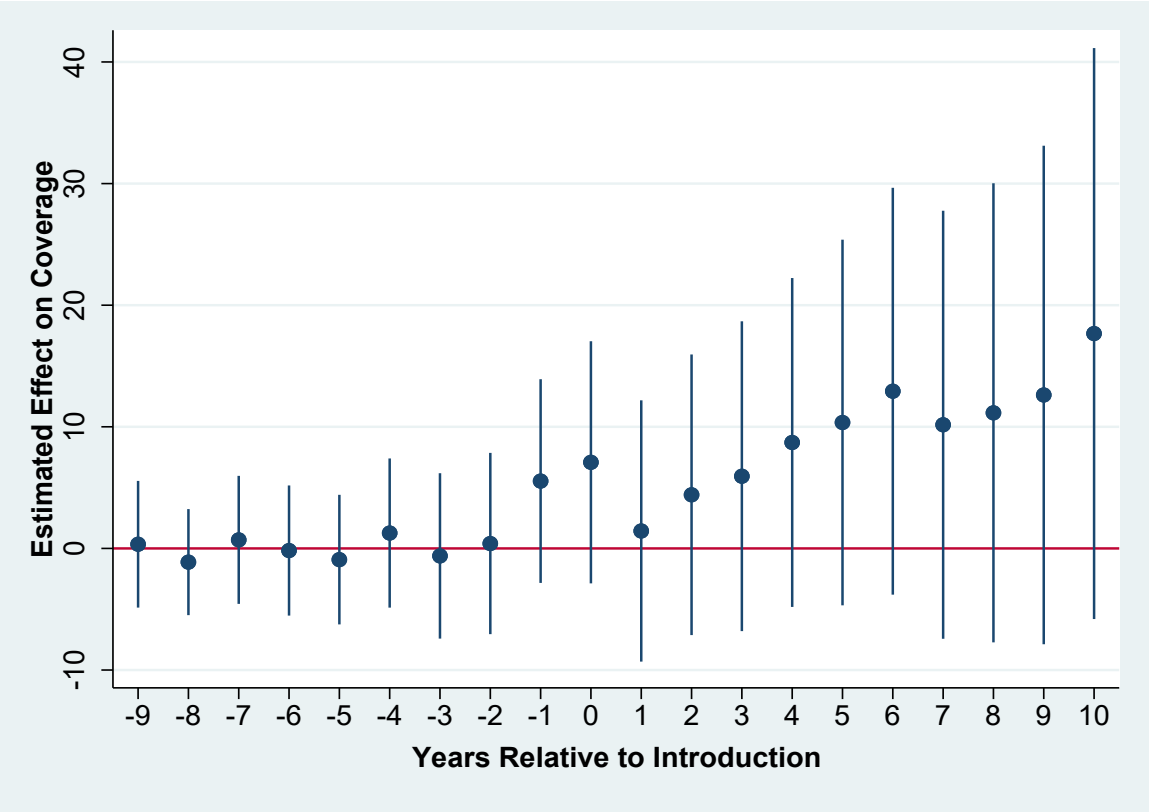
Figure 1: Impact of Gavi-funded introduction of a vaccine on coverage rate



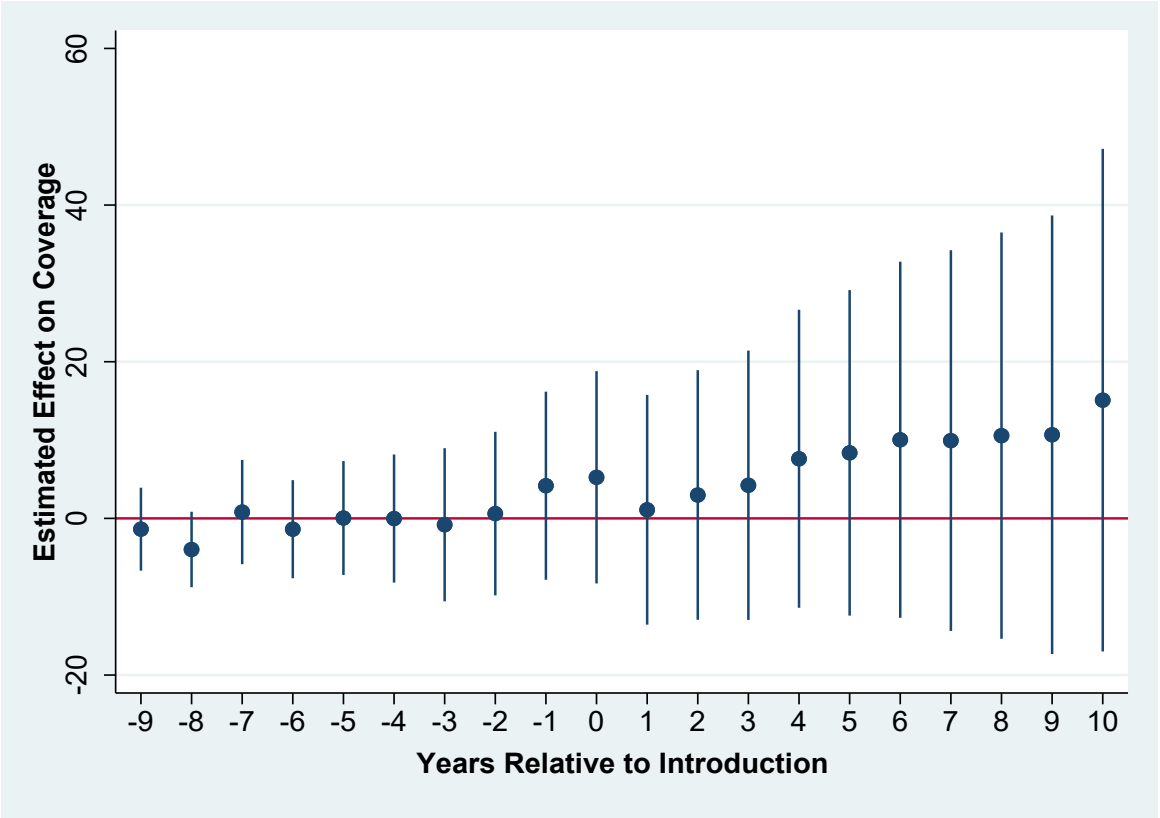
Note: This figure plots the impact of Gavi-funded introduction of a vaccine on coverage rates. Observations are at the country X vaccine X dose X cohort level. The regression includes country X vaccine, country X cohort, and vaccine X cohort fixed effects. 95% confidence intervals are estimated from robust standard errors, clustered by country.

Figure 2: Impact of Gavi-funding of any vaccine on coverage of other vaccines



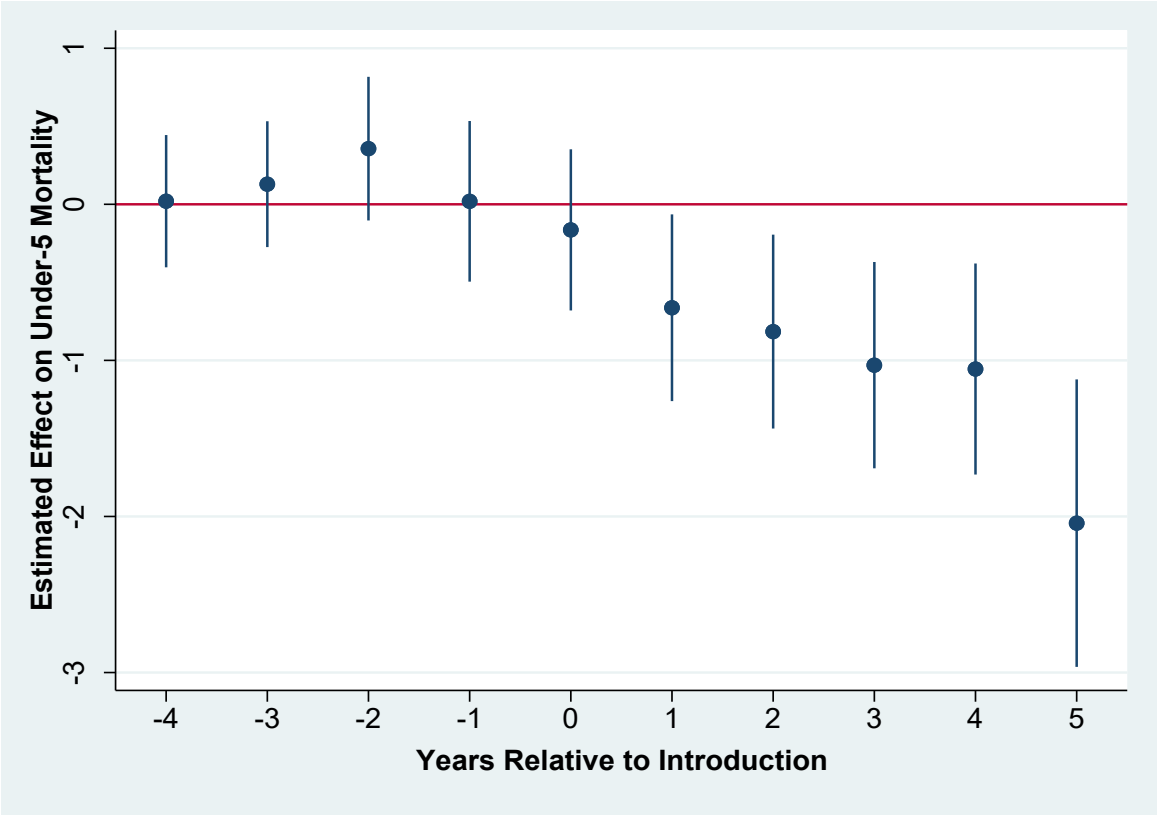
Note: This figure plots the impact of Gavi-funded introduction of any vaccine on coverage rates for vaccines not funded by Gavi yet. Observations are at the country X vaccine X dose X cohort level. The regression includes country X vaccine and vaccine X cohort fixed effects as well as country-specific trends. 95% confidence intervals are estimated from robust standard errors, clustered by country.

Figure 3: Impact of Gavi-funding of any vaccine on coverage of BCG



Note: This figure plots the impact of Gavi-funded introduction of any vaccine on coverage rates for BCG (which Gavi does not fund). Observations are at the country X cohort level. The regression includes country and cohort fixed effects as well as country-specific trends. 95% confidence intervals are estimated from robust standard errors, clustered by country.

Figure 4: Impact of Gavi-funded introduction of a vaccine on child mortality by cause



Note: This figure plots the impact of Gavi-funded introduction of a vaccine on child mortality rates for primarily-linked causes of death. Observations are at the country X cause of death X year level. Only causes of death related to a Gavi-funded vaccine are included in the sample. The regression includes country X cause of death, country X year, and cause of death X year fixed effects. 95% confidence intervals are estimated from robust standard errors, clustered by country.

Table 1: Number of countries introducing a Gavi-funded vaccine, by year and vaccine

Year	Inactivated Polio Vaccine	Japanese Encephalitis	Measles	Meningitis A	Measles-rubella	Pentavalent (Diphtheria, Tetanus, Pertussis, Hepatitis B, Haemophilus influenzae type B)	Pneumococcal	Rotavirus	Yellow Fever	Human Papillomavirus
Pre-2003						11			7	
2003									3	
2004									4	
2005						6			2	
2006	1					3				
2007			1			4			1	
2008			1			18		1	2	
2009						17	2	1		
2010				3		3	1	2		
2011				3	1	3	13	1	1	
2012			7	4	1	5	8	7		
2013			6	2	4	2	14	6		6
2014	3		5	3	6	1	8	16	1	8
2015	39	1	6	1	4		8	4		7
2016	14	2		3	5		3	3		6
2017	2	1	1	2	5		1	3		9
2018	15	1	1	1	7		1	2		
2019	2		4	1	2		1			1
Total	76	5	32	23	35	73	60	46	21	37

Note: This table lists the number of countries that introduced, with Gavi support, each vaccine in each year.

Source: GAVI

Table 2: Summary statistics on vaccine coverage

	Mean coverage					
Vaccine	1985-89	1990-94	1995-99	2000-04	2005-09	2010-14
BCG vaccine	75.82	82.89	81.56	83.96	88.37	90.68
DTP vaccine	68.74	75.21	73.91	77.85	80.65	83.99
Hepatitis B vaccine		75.18	81.39	82.18	76.97	83.34
HiB vaccine			96.2	81.16	80.25	84.34
Inactivated polio vaccine					97	83.68
Measles containing vaccine	59.72	67.89	68.56	74.46	75.01	78.05
Pneumococcal conjugate vaccine					59.24	69.48
Polio vaccine	68.7	75.47	75.41	79.59	81.61	83.63
Rubello containing vaccine					86.5	85.29
Rotavirus vaccine					60.18	68.74
Tetanus vaccine			44.7	40.05	7	57.19
Yellow Fever vaccine	32.67	36.19	29.15	56.19	62.69	67.56

Note: This table presents average coverage rates by vaccine for the countries and cohorts for which survey data is available. Some averages (such as the rates for IPV and tetanus between 2005 and 2009) are based on very few data points. In this table (but not in the regressions), we average coverage rates across doses when available. Our data includes estimates of coverage for cohorts born from 1979 to 2016, but 96% of the observations are from 1985 to 2014.

Table 3: Summary statistics on causes of death

	Mean # deaths per 1000 live births					
Cause of Death	2000 (1)	2005 (2)	2010 (3)	2015 (4)	Primarily-linked Gavi-funded vaccine (5)	Any linked Gavi-funded vaccines (6)
Birth asphyxia and birth trauma	0.51	0.44	0.39	0.37		
Congenital anomalies	1.91	1.66	1.53	1.43		
Diarrheal diseases	6.27	4.26	3.05	2.25	Rotavirus	Rotavirus, Measles
HIV/AIDS	2.32	2.05	1.13	0.63		
Injuries	2.32	2.05	2.58	1.85		
Malaria	4.64	3.74	2.67	1.7		
Measles	2.6	0.96	0.45	0.59	Measles, Measles-Rubella	Measles, Measles-Rubella
Meningitis/encephalitis	1.63	1.27	0.78	0.5	Meningitis A, Japanese encephalitis	Meningitis A, Japanese encephalitis, Pneumococcal, Pentavalent
Other communicable, perinatal and nutritional conditions	3.26	2.73	2.44	2.28		
Other non-communicable diseases	2.34	2	1.86	1.71		
Prematurity	0.74	0.62	0.56	0.53		
Acute lower respiratory infections	7.9	6.25	4.76	3.6	Pneumococcal, Pentavalent	Pneumococcal, Pentavalent, Measles

Note: This table presents the average number of deaths among children 1-59 months old per 1000 live births attributed to specific causes in each year. Column (5) assigns vaccines to the cause of death they are most closely linked to. Column (6) lists any vaccine that can impact deaths attributed to each cause.

Table 4: Impact of Gavi-funded introduction of a vaccine on coverage rate

Post designation:	Introduction Dates			First Year Funded		
Funded vaccines:	All	Pre-existing	New	All	Pre-existing	New
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: All countries						
Post introduction of this vaccine	3.39***	2.30***	19.90***	4.03***	2.90***	20.86***
	(0.88)	(0.76)	(7.51)	(0.96)	(0.92)	(7.01)
Number of obs.	8641	8528	7364	8641	8518	7281
R-squared	0.828	0.830	0.838	0.828	0.830	0.840
Dep. var. mean	76.92	76.89	76.32	76.92	76.93	76.39
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)						
Post introduction of this vaccine	2.70***	2.24***	10.42	3.85***	3.20***	13.89*
	(0.90)	(0.80)	(8.36)	(1.04)	(1.03)	(7.14)
Number of obs.	6739	6626	5467	6739	6616	5383
R-squared	0.839	0.840	0.851	0.839	0.840	0.853
Dep. var. mean	75.58	75.53	74.48	75.58	75.58	74.54

Note: This table presents estimates of the impact of Gavi-funded introduction of a vaccine on coverage rates using survey data. Observations are at the country X vaccine X dose X cohort level. To determine the first year of Gavi support, Columns (1)-(3) use launch dates while Columns (4)-(6) use vaccine-specific line items in the funding data. All regressions include country X vaccine, country X cohort, and vaccine X cohort fixed effects. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%

Table 5: Impact of Gavi-funded introduction of any vaccine on coverage of other vaccines

Post designation:	Introduction Dates		First Year Funded	
	All vaccines not yet funded	BCG	All vaccines not yet funded	BCG
	(1)	(2)	(3)	(4)
Panel A: All countries				
Post any introduction	0.68	0.66	0.41	-1.07
	(1.48)	(1.43)	(2.62)	(3.42)
Number of obs.	7270	1138	7270	1138
R-squared	0.734	0.836	0.734	0.836
Dep. var. mean	76.31	83.46	76.31	83.46
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)				
Post any introduction	0.90	0.03	-1.12	-2.74
	(1.52)	(1.37)	(2.87)	(3.94)
Number of obs.	5367	922	5367	922
R-squared	0.740	0.831	0.740	0.831
Dep. var. mean	74.41	82.85	74.41	82.85

Note: This table presents estimates of the impact of Gavi-funded introduction of any vaccine on coverage rates for vaccines not funded by Gavi yet, using survey data. Observations are at the country X vaccine X dose X cohort level. To determine the first year of Gavi support, Columns (1)-(2) use launch dates while Columns (3)-(4) use vaccine-specific line items in the funding data. All regressions include country X vaccine and vaccine X cohort fixed effects in addition to country-specific trends. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%

Table 6: Impact of Gavi-funded introduction of vaccine on child mortality from primarily-linked causes

	Affected causes of death					Only causes of death related to a Gavi-funded vaccine
	All	Respiratory	Diarrheal diseases	Measles	Meningitis/ Encephalitis	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: All countries						
Post introduction of related vaccine	-2.34***	-3.30***	-2.87***	-1.02***	-0.58	-1.15***
	(0.26)	(0.35)	(0.48)	(0.38)	(0.39)	(0.20)
Number of obs.	41904	41533	40986	40962	40916	13968
R-squared	0.878	0.880	0.876	0.876	0.877	0.936
Dep. var. mean	2.05	2.05	1.94	1.93	1.93	2.74
Num affected obs	1071	700	155	131	85	1071
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)						
Post introduction of related vaccine	-1.32***	-1.85***	-1.60***	-1.03**	-0.50	-0.58***
	(0.22)	(0.35)	(0.50)	(0.42)	(0.39)	(0.18)
Number of obs.	20304	19933	19386	19362	19316	6768
R-squared	0.878	0.879	0.876	0.877	0.877	0.931
Dep. var. mean	3.50	3.52	3.34	3.32	3.33	4.98
Num affected obs	1071	700	155	131	85	1071

Note: This table presents estimates of the impact of Gavi-funded introduction of a vaccine on child mortality from primarily-linked causes. Observations are at the county X cause of death X year level. All regressions include country X cause of death, country X year, and cause of death X year fixed effects. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%

Table 7: Impact of Gavi-funded introduction of a vaccine on child mortality from any linked causes

		Affected causes of death				Only causes of death related to a Gavi-funded vaccine
	All	Respiratory	Diarrheal diseases	Measles	Meningitis/ Encephalitis	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: All countries						
Number of introduced related vaccines	-1.30***	-2.06***	-2.05***	-1.17***	-0.23**	-0.38**
	(0.14)	(0.21)	(0.25)	(0.39)	(0.09)	(0.17)
Number of obs.	41904	40840	40361	40262	40834	13968
R-squared	0.878	0.881	0.877	0.877	0.877	0.935
Dep. var. mean	2.05	2.05	1.95	1.94	1.93	2.74
Num affected obs	1176	431	174	131	440	1176
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)						
Number of introduced related vaccines	-0.89***	-1.38***	-1.14***	-1.09**	-0.25**	-0.24
	(0.15)	(0.23)	(0.29)	(0.43)	(0.11)	(0.15)
Number of obs.	20304	19240	18761	18662	19234	6768
R-squared	0.878	0.880	0.876	0.877	0.877	0.930
Dep. var. mean	3.50	3.59	3.41	3.38	3.33	4.98
Num affected obs	1176	431	174	131	440	1176

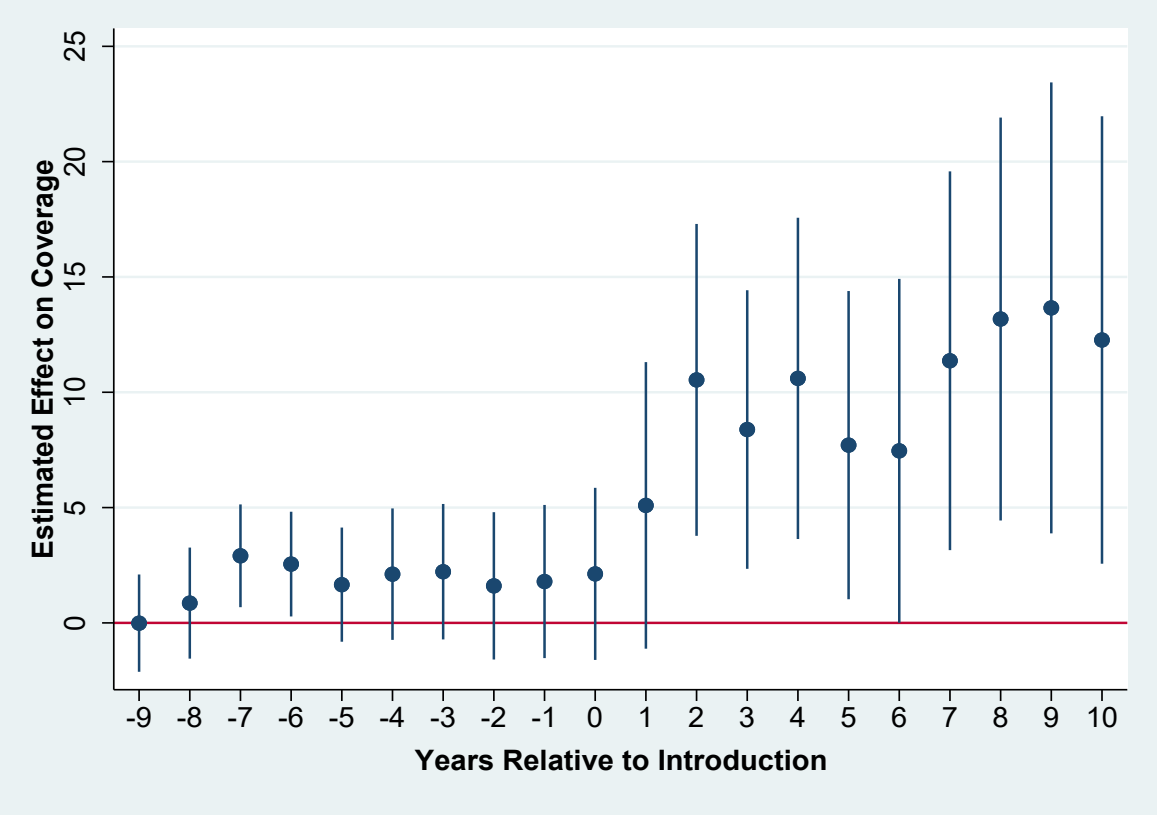
Note: This table presents estimates of the impact of Gavi-funded introduction of a vaccine on child mortality from any linked causes. Observations are at the county X cause of death X year level. All regressions include country X cause of death, country X year, and cause of death X year fixed effects. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%

Table 8: Impact of Gavi-funded introduction of any vaccine on coverage of unrelated causes of death

Post designation:	Introduction Dates		First Year Funded	
Causes of death included:	Not (yet) affected	Never affected	Not (yet) affected	Never affected
	(1)	(2)	(3)	(3)
Panel A: All countries				
Post any introduction	-0.87***	-0.50***	-1.25***	-0.59***
	(0.11)	(0.09)	(0.17)	(0.12)
Number of obs.	40131	27936	40131	27936
R-squared	0.856	0.835	0.856	0.835
Dep. var. mean	1.94	1.70	1.94	1.70
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)				
Post any introduction	-0.51***	-0.16	-0.53***	-0.04
	(0.13)	(0.12)	(0.20)	(0.14)
Number of obs.	18531	13536	18531	13536
R-squared	0.858	0.837	0.858	0.837
Dep. var. mean	3.40	2.76	3.40	2.76

Note: This table presents estimates of the impact of Gavi-funded introduction of any vaccine on child mortality from unrelated causes. Observations are at the county X cause of death X year level. All regressions include country X cause of death and cause of death X year fixed effects in addition to country-specific trends. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%

Figure A1: Impact of Gavi-funded introduction of a vaccine on coverage rate



Note: This figure plots the impact of Gavi-funded introduction of a vaccine on coverage rates. Observations are at the country X vaccine X dose X cohort level. Among the treated vaccines, only those related to causes of death in the GHO data are included (rotavirus, measles, pneumococcal and HiB from the pentavalent vaccine). The regression includes country X vaccine, country X cohort, and vaccine X cohort fixed effects. 95% confidence intervals are estimated from robust standard errors, clustered by country.

Table A1: Number of countries newly receiving Gavi vaccine-specific funding, by year and vaccine

Year	Inactivated Polio Vaccine	Japanese Encephalitis	Measles	Meningitis A	Measles-rubella	Pentavalent (Diphtheria, Tetanus, Pertussis, Hepatitis B, Haemophilus influenzae type B)	Diphtheria, Tetanus, Pertussis, Hepatitis B	Diphtheria, Tetanus, Pertussis, Haemophilus influenzae type B	Hepatitis B	Haemophilus influenzae type B
2001						2	5		7	
2002						4	2	1	12	1
2003							1		8	
2004								2	3	
2005						7	3		1	
2006						2	3		2	
2007			1			3	2	1		1
2008			1			21		1		
2009						17				
2010						2				
2011				3		3				
2012			8	4		5				
2013			5	2	6	2				
2014	2		4	4	4	1				
2015	68	1	8	2	6					
2016	1	2		5	4					
2017		2		1	10					
2018			3	2	2					
2019			2	1	4					
Total	71	5	32	24	36	69	16	5	33	2

Note: This table lists the number of countries that received Gavi funding in a vaccine-specific sub-category for the first time each year.
Source: GAVI

Table A1: (continued)

Year	Diphtheria, Tetanus	Pneumococcal	Rotavirus	Yellow Fever	Human Papillomavirus	Typhoid
2001				3		
2002				3		
2003				5		
2004				4		
2005						
2006						
2007						
2008			2	2		
2009		2	2			
2010		6				
2011		9	1			
2012		9	7			
2013		14	10		7	
2014		10	12	1	11	
2015		5	5		8	
2016		1	1		3	
2017		1	3		7	
2018	1	1	4			
2019					3	1
Total	1	58	47	18	39	1

Table A2: Impact of Gavi-funded introduction of a vaccine on WHO estimates of coverage rate

Post designation:	Introduction Dates			First Year Funded		
Funded vaccines:	All	Pre-existing	New	All	Pre-existing	New
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: All countries						
Post introduction of this vaccine	4.13***	1.98***	43.78***	3.25***	1.70**	45.35***
	(0.67)	(0.62)	(4.65)	(0.73)	(0.71)	(5.96)
Number of obs.	51661	49872	1190	51661	49872	1190
R-squared	0.845	0.851	0.912	0.844	0.851	0.907
Dep. var. mean	82.75	82.91	79.69	82.75	82.91	79.69
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)						
Post introduction of this vaccine	4.16***	1.56**	43.04***	3.33***	1.30	44.39***
	(0.75)	(0.69)	(4.76)	(0.82)	(0.80)	(6.13)
Number of obs.	23800	22962	622	23800	22962	622
R-squared	0.866	0.872	0.928	0.865	0.872	0.918
Dep. var. mean	76.29	76.31	79.32	76.29	76.31	79.32

Note: This table presents estimates of the impact of Gavi-funded introduction of a vaccine on coverage rates estimated by the WHO. Observations are at the country X vaccine X dose X cohort level. To determine the first year of Gavi support, Columns (1) to (3) use launch dates while Columns (4)-(6) use vaccine-specific line items in the funding data. Column (7) uses the approved funds per capita. Panel A includes all countries, while Panel B includes Gavi-recipient countries and countries with slighly higher GNI per capita up to $3500 (2010 US$). All regressions include country X vaccine, country X cohort, and vaccine X cohort fixed effects. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%

Table A3: Robustness checks on impact of Gavi-funded introduction of a vaccine on coverage rate

Post designation:	Introduction Dates					First Year Funded				
Robustness check:	Excluding POL & HEB-BD	Excluding Measles & Rubella	Linear country X vaccine trends	Region X vaccine X cohort fixed effects	WHO region X vaccine X cohort fixed effects	Excluding POL & HEB-BD	Excluding Measles & Rubella	Linear country X vaccine trends	Region X vaccine X cohort fixed effects	WHO region X vaccine X cohort fixed effects
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: All countries										
Post introduction of this vaccine	4.51***	3.96***	3.40***	2.15**	1.57	4.64***	4.60***	4.04***	3.22***	3.60***
	(1.16)	(0.97)	(0.93)	(0.95)	(1.04)	(1.26)	(1.09)	(1.02)	(1.09)	(1.21)
Number of obs.	6351	7404	8641	8435	8413	6351	7404	8641	8435	8413
R-squared	0.861	0.817	0.828	0.836	0.839	0.861	0.817	0.828	0.836	0.839
Dep. var. mean	76.89	78.00	76.92	76.74	76.74	76.89	78.00	76.92	76.74	76.74
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)										
Post introduction of this vaccine	3.54***	3.38***	2.70***	2.10**	1.57	4.10***	4.56***	3.86***	3.62***	4.22***
	(1.28)	(1.01)	(0.95)	(1.04)	(1.14)	(1.43)	(1.21)	(1.10)	(1.21)	(1.37)
Number of obs.	4952	5807	6739	6672	6642	4952	5807	6739	6672	6642
R-squared	0.870	0.827	0.838	0.847	0.851	0.870	0.828	0.839	0.848	0.851
Dep. var. mean	75.65	76.72	75.58	75.54	75.54	75.65	76.72	75.58	75.54	75.54

Note: This table presents estimates of the impact of Gavi-funded introduction of a vaccine on coverage rates. Observations are at the country X vaccine X dose X cohort level. All regressions include country X vaccine, country X cohort, and vaccine X cohort fixed effects. Columns (4) and (9) include fixed effects for region X vaccine X cohort, where the world is divided into 9 regions, based loosely on the WHO regions. Columns (5) and (10) include these fixed effects using WHO regions but we lose power since the variation is at the country X vaccine X cohort level. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%

Table A4: Impact of Gavi-funded introduction of vaccine on under-five mortality from primarily-linked causes

		Affected causes of death				Only causes of death related to a Gavi-funded vaccine
	All	Respiratory	Diarrheal diseases	Measles	Meningitis/ Encephalitis	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: All countries						
Post introduction of related vaccine	-2.24***	-3.14***	-2.80***	-0.66*	-0.27	-1.19***
	(0.26)	(0.34)	(0.48)	(0.36)	(0.28)	(0.21)
Number of obs.	41904	41551	41050	41008	40959	13968
R-squared	0.878	0.880	0.876	0.876	0.877	0.936
Dep. var. mean	2.05	2.04	1.94	1.93	1.94	2.74
Num affected obs	1016	663	162	120	71	1016
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)						
Post introduction of related vaccine	-1.11***	-1.59***	-1.52***	-0.60	-0.17	-0.54***
	(0.22)	(0.34)	(0.50)	(0.40)	(0.28)	(0.19)
Number of obs.	20304	19951	19450	19408	19359	6768
R-squared	0.877	0.879	0.876	0.877	0.877	0.931
Dep. var. mean	3.50	3.52	3.34	3.32	3.33	4.98
Num affected obs	1016	663	162	120	71	1016

Note: This table presents estimates of the impact of Gavi-funded introduction of a vaccine on child mortality from primarily-linked causes. Observations are at the county X cause of death X year level. The first year of Gavi support is determined from vaccine-specific line items in the funding data. All regressions include country X cause of death, country X year, and cause of death X year fixed effects. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%

Table A5: Robustness of impact of Gavi-funded introduction of vaccine on child mortality from linked causes

	Linear country X cause of death trends (1)	Region X vaccine X year fixed effects (2)	WHO region X vaccine X year fixed effects (3)	Ln of child mortality (5)	Total under-5 mortality (4)	Under <28 day mortality (6)
Panel A: All countries						
Post introduction of related vaccine	-2.36***	-1.75***	-1.76***	-0.23***	-1.77***	0.04
	(0.27)	(0.23)	(0.24)	(0.03)	(0.24)	(0.02)
Number of introduced related vaccines						
Number of obs.	41904	41904	41904	32114	45396	45396
R-squared	0.877	0.899	0.909	0.960	0.929	0.983
Dep. var. mean	2.05	2.05	2.05	0.02	2.05	1.22
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)						
Post introduction of related vaccine	-1.33***	-1.06***	-1.12***	-0.16***	-1.12***	0.01
	(0.23)	(0.19)	(0.21)	(0.04)	(0.21)	(0.02)
Number of introduced related vaccines						
Number of obs.	20304	20304	20304	18089	21996	21996
R-squared	0.877	0.897	0.906	0.958	0.920	0.990
Dep. var. mean	3.50	3.50	3.50	0.57	3.50	1.87

Note: This table presents estimates of the impact of Gavi-funded introduction of a vaccine on child mortality from primarily-linked causes. Observations are at the county X cause of death X year level. All regressions include country X cause of death, country X year, and cause of death X year fixed effects. Column (2) includes fixed effects for region X vaccine X cohort, where the world is divided into 9 regions, based loosely on the WHO regions. Column (3) includes these fixed effects using WHO regions. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%

Table A6: Sensitivity to cause of death errors

Post designation:	Introduction Dates		First Year Funded	
	Collapsing affected causes and unaffected causes (1)	All-cause under-5 mortality (2)	Collapsing affected causes and unaffected causes (3)	All-cause under-5 mortality (4)
Panel A: All countries				
Post any introduction X affected causes	-5.07***		-8.12***	
	(1.05)		(1.29)	
Post any introduction		-15.42***		-19.82***
		(1.59)		(2.57)
Number of obs.	6984	3402	6984	3402
R-squared	0.972	0.950	0.973	0.950
Dep. var. mean	12.29	41.81	12.29	41.81
Panel B: Gavi-recipient or 2000 GNI per capita < 3500 (2010 US$)				
Post any introduction X affected causes	-5.07***		-8.12***	
	(1.05)		(1.29)	
Post any introduction		-15.42***		-19.82***
		(1.59)		(2.57)
Number of obs.	6984	3402	6984	3402
R-squared	0.972	0.950	0.973	0.950
Dep. var. mean	12.29	41.81	12.29	41.81

Note: This table presents estimates of the impact of Gavi-funded introduction of any vaccine on mortality from affected causes in Columns (1) and (3) and all-cause mortality in Columns (2) and (4). Observations are at the county X cause of death X year level. All regressions include country X cause of death and cause of death X year fixed effects. Columns (1) and (3) include country X year fixed effects while Columns (2) and (4) include country-specific trends. Robust standard errors, clustered by country, are shown in parentheses. * 10% ** 5% *** 1%