



Impact of vaccine stockouts on immunization coverage in Nigeria

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ABSTRACT

Improving immunization coverage requires creating reliable supply of vaccines and immunization supplies; trained and incentivized health workers; and strategies to improve the demand for immunization. Yet, the interplay of demand and supply side factors on immunization coverage has not been evaluated in literature with data. We use data from Nigeria and a mixed-effects general linear model to estimate the effect of vaccine availability on routine immunization coverage and to identify demand and health system factors which affect this relationship. We find that when vaccine stockouts occur at Local Government Area stores in Nigeria, they significantly decrease the number of children immunized, and for most vaccines, the effect lasts for several months after a stockout. Some of the demand lost when a stockout occurs is recovered over the following six months as children catch up with the regimen. The magnitude of the impact varies across different vaccines.

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1. Introduction

Immunization is one of the most cost-effective ways of improving child survival in developing countries [1,2]. There has been significant progress toward immunization targets in recent years, particularly with the uptake of new and underused vaccines [3]. However, many children especially in low and lower middle-income countries remain under immunized or unimmunized [3–6]. Improving immunization coverage requires reliable supply of vaccines and immunization supplies, trained and incentivized health workers, good program management, and strategies to improve the demand for immunization. Previous studies have shown the impact of various demographic and health system indicators on immunization coverage rates [7–9], but these studies make simplifying assumptions about vaccine supply—they do not take the availability of vaccines into account. Similarly, studies have captured the impact of investments in market-shaping and supply chain interventions to ensure supply [10] on the availability/stockouts of vaccines in health facilities [11–15], but the impact of stockout reduction on immunization coverage has not been fully investigated. In order to achieve immunization coverage targets it is important to “unbundle” the context-specific demand and supply barriers to immunization and design interventions accordingly.

Banerjee et al. (2010) [16] show that providing demand incentives for immunization along with improving the supply of services is more cost effective than improving the supply of services alone. It is therefore important to understand the complementarities between demand and supply side activities to achieve maximum value for money from investments in immunization.

Realizing that vaccine stockouts are still prevalent across many regions of the world [17], efforts are underway to improve the supply chain [18]. De Boeck et al. (2018) [19] provide a review of the characteristics of and challenges in vaccine supply chains in developing countries. Countries in sub-Saharan Africa experience a higher incidence of vaccine stockouts than any other part of the world and these stockouts often interrupt immunization services [17]. As a result many efforts are underway in sub-Saharan Africa to improve vaccine supply chains [20]. For example, Sarley et al. (2017) [10] describe supply chain improvement programs in Nigeria designed to address consistent stockouts and under-supply (one state's district-level warehouses were stocked out of most vaccines more than 80% of the time). There is some recent evidence in the context of vaccine delivery in Nigeria that after a supply chain redesign, which effectively reduced stockouts, the number of children being vaccinated increased [14]. However, the authors do not control for confounding factors such as changes in the catchment population, demographics, and the strength of the primary health care system.

As new vaccines are developed and introduced into national immunization programs, the supply chain burden of those

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programs is increasing. According to one set of estimates, between 2010 and 2020 four times the volume of vaccines will need to be managed by the immunization supply chain globally and health workers will administer six times as many doses per person [20,21]. Multifold increases in volume and doses will also result in higher costs per fully immunized child. Understanding the relationship between improvements in supply chain performance and immunization coverage will be critical to ensuring adequate funding and prioritization of supply chain improvement programs.

In this paper, we seek to answer the following research question: *Do stockouts of vaccines at the service delivery point affect immunization coverage? If so, how? What factors impact the size of the effect?*

When a vaccine stockout occurs, some of the lost demand is recovered through (routine immunization) catchup and campaigns. Also, when parents/family members of a child observe a stockout at their health facility they may tell others that the facility has no vaccines, which may affect the others' decision to take their children for immunization in future months. So answering the above question is not straight forward.

We use data from Nigeria to attempt to answer the research question. Our findings apply most directly to Gavi-eligible countries in sub-Saharan Africa. Validity of the findings of this study is limited to countries where vaccine procurement is timely, adequate supply is available, and the main barriers to ensuring availability of vaccines exist somewhere along the multi-level public sector distribution system.

We use a mixed-effects general linear model and data from immunization programs to estimate the effect of vaccine availability on routine immunization coverage in Nigeria and to identify factors which affect this relationship. We account for demographic, health system, and vaccine supply effects.

1.1. Childhood immunization in Nigeria

Immunization coverage in Nigeria has fluctuated over time due to changes in public health care priorities, funding, governance, and security. In the early 1990s Nigeria achieved 81.5% universal childhood immunization coverage but coverage has steadily declined since [22]. A recent World Health Organization report states that Nigeria's immunization programs suffer due to health-care personnel shortages, lack of funds, poor promotion, insecurity, and lack of quality data [23]. According to national survey indicators, Nigeria consistently has some of the lowest immunization coverage rates in the world. The 2017 National Immunization Coverage Survey estimated that only 23% of children (aged 12–23 months) received all recommended immunizations by their first birthday, with only 5% of children in the poorest wealth quintile fully immunized. The same survey showed that 34 out of the 37 states and the capital territory had a full vaccination rate lower than 50% [24].

In recent years, donors and the Nigerian government have worked to improve the supply of vaccines. Efforts have focused on improving cold chain equipment capacity, strengthening data management systems, building supply chain capacity within the Nigerian government, and redesigning distribution to improve effectiveness.

1.1.1. Immunization programs

Government and donor-funded programs for immunization in Nigeria take two primary forms—routine immunization and immunization campaigns. Routine immunization programming has become a strategic priority of the National Primary Healthcare Development Agency. The routine immunization system administers at least seven recommended vaccines in primary health care facilities throughout Nigeria. The recommended routine immu-

Table 1

Recommended routine immunization schedule for children in Nigeria.

Month	Recommended Immunization
0	Bacillus Calmette-Guérin (BCG), Hepatitis B, Oral Poliovirus ^a
1.5	Pentavalent, Oral Poliovirus, Pneumococcal Conjugate
2.5	Pentavalent, Hepatitis B, Oral Poliovirus
3.5 or 4	Pentavalent, Hepatitis B, Oral Poliovirus, Pneumococcal Conjugate
9	Measles, Yellow Fever

^a We investigate the stockout-coverage relationship for bi-valent and tri-valent oral poliovirus vaccines (bOPV and tOPV, respectively) only. We consider both tOPV and bOPV as oral poliovirus vaccines and aggregate the data as such. This is valid because bi-valent OPV was phased in as a replacement to tri-valent OPV in 2016. We do not include tri-valent inactivated poliovirus vaccine (IPV) in the analysis because the necessary data on IPV immunization coverage was not available. IPV is recommended in Nigeria in addition to bOPV and therefore its exclusion does not affect the results for oral poliovirus vaccine.

nization schedule [25] for children in Nigeria is shown in Table 1. Vaccines which require multiple doses are called multi-dose regimens, the final dose of which is called the regimen-completing dose (e.g., the third dose of pentavalent). The recommended schedule includes three single-dose and four multi-dose vaccines.

Children arriving at a facility to receive a vaccine that is unavailable are typically instructed to return to the facility in the coming weeks (when a restock is expected) or, in some cases, to wait until their next immunization visit when they can receive the missed dose.

Immunization campaigns (also known as “intensified activities”) take place as a supplement to routine immunization. During campaigns, health workers travel to households and immunize eligible children on-site. Campaigns may occur regularly to improve low coverage rates or may be conducted to contain a disease outbreak.

1.1.2. Nigeria's vaccine supply chain

Vaccines are procured internationally and most are stored in a national warehouse upon arrival. Vaccines then move through a combination of regional, state, satellite (multi-district) and/or district (also known as “Local Government Areas”, or “LGAs” in Nigeria) warehouses before being transported to a health facility.

2. Methods

2.1. Conceptual model

We first develop a conceptual model of the relationship between vaccine availability and routine immunizations (Fig. 1) using existing literature and interviews with health experts. Routine immunizations is the number of children who receive vaccines via the routine immunization system and it is affected by both the supply of vaccines and the demand for immunization. We use absolute immunization numbers (number of children immunized) while taking into account the number of children eligible for immunization. Vaccine stock unavailability (stockouts) may reduce the number of children immunized in the short term and in the long term. In the short term, children are unable to be vaccinated if there are no available vaccines at the clinic. In the long term, vaccine unavailability interrupts immunization regimens and may decrease people's willingness to bring their children to clinics if they expect that no vaccines will be available. Health experts in Nigeria suggest that immunization campaigns may increase or decrease demand for current and future routine immunization. Campaigns may increase demand through sensitization. Campaigns may decrease demand because people begin to expect campaigns will come to their house; they may wait to take their child to a clinic for vaccination or fail to take them altogether because

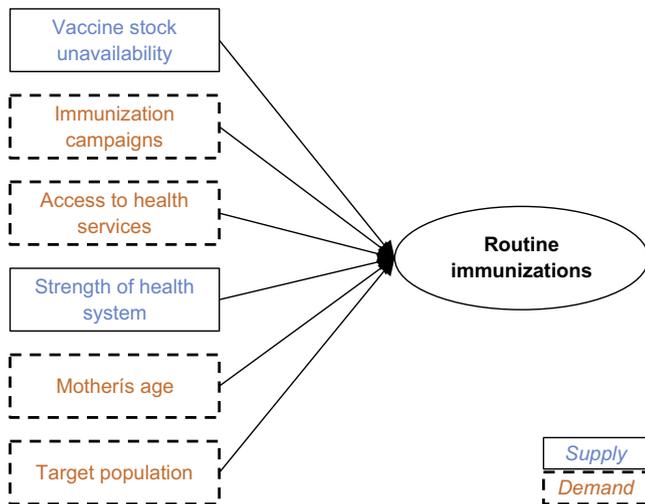


Fig. 1. Conceptual model of the relationship between vaccine availability and routine immunizations.

they expect a campaign. Other forms of demand generation (e.g., sensitization programs) may exist, but we do not include them in our model because no systematic data is available.

Literature shows (and health experts confirm) several health system and demographic factors affect routine immunization [4,5]. Esposito et al. (2014) [7], Topuzoglu et al. (2007) [26], and Banerjee et al. (2010) [16] show that access to health services affects the use of immunization services. If parents are able to easily access a health care center they are more likely to use its services, more so if they are offered incentives [16]. The strength of the health system also affects the use of immunization services [26]. Strength of primary health care system depends on the population's access to primary care (i.e., absence of financial and geographic barriers) and the availability of key inputs for high quality service delivery at the health clinic (including drugs and supplies, facility infrastructure, information systems, workforce, funds, and well-designed operational processes). Parents are less likely to use a primary health care facility for their children if the primary care system is lacking in any of these inputs. The age of a child's mother also affects the uptake of vaccination services [8,27,28]. Finally, as the population grows more children are eligible for immunization—the target population for immunization affects the number of children immunized.

Additional factors such as health care worker density [9], mother's education or literacy level [8,29–31], ethnicity [8], economic status [31], and cultural or religious beliefs [32] have also been shown to affect or be related to immunization coverage. There is no evidence that these variables are correlated with our main explanatory variable of interest (vaccine unavailability), and therefore omitting them does not bias our results. We later control for factors that are unobserved and specific to each LGA with our model estimation method.

2.2. Data

We use stock availability data from the supply chain that delivers vaccines to health facilities. The National Immunization Supply Chain Management Information System (NISC-mis)/Navision captures stock and flow data at the National, Zonal, State, and LGA level. Reporting of stock data from the LGA level into Navision is at the end of every week. LGA-level stock data is based on manual data entry by health system staff and the data may not reflect the actual stock on hand if staff do not conduct the weekly physical

inventory count. However, this data is the only systematic data available at present which captures vaccine stock availability at LGAs across the country. The amount of invalid or missing stock data in Navision has decreased since 2015 (see: Appendix), indicating that reporting consistency has improved.

We measure vaccine availability as the number of weeks in each month where stockouts (a stock level equal to zero) were reported by the LGA. This is a service level metric instead of a fill rate metric and as such, our results are limited to stockouts. Unfortunately, with the level of aggregation in our data we cannot distinguish between a stockout of one day or a stockout of multiple days, and therefore we cannot make definitive claims about the impact of the severity and duration of the stockout (within a week) on immunization coverage. Even with weekly aggregated data on any instance of a stockout during the week, we are able to detect a significant impact of stockouts on immunization coverage and this gives us confidence in our results.

We use data regarding the immunizations of children in their first year of life and measure immunizations by using the total number of children under one year of age who are immunized with each vaccine (any dose) in each month. We aggregate all regimen doses because we found evidence that the reporting of different regimen doses is skewed to increase the number of regimen-completing doses.

We also collect the health system and demographic data detailed above which might affect the translation of vaccine availability to routine immunization coverage. The data we use for health system access, strength, and mother's age are held constant over our time horizon. They take into account the general difficulty (or ease) in accessing the health care system, the health system's reputation and functionality in different areas, and basic demographic indicators. We use the percent of women reporting at least one problem accessing health care as our measure of health system access. We use the average proportion of correct diagnoses (diagnostic accuracy) provided by clinical staff in response to a series of five vignettes as our measure of health system strength.

Table 2 contains a description of the variables we use in our model. A full description of the data sources considered and used for each variable is found in the Appendix. Data from 2015 to 2016 are included.

2.3. Model-building process

We use a mixed-effects model to estimate the effect of stock availability on immunization coverage while accounting for unmeasured factors that could affect that relationship and that are unique to each LGA or month. This is possible due to the granularity of our panel dataset (LGA-level) and the long time horizon over which it was collected (two years). To improve the model, we also include the control variables described above that may affect immunization coverage (health system access, strength, mother's age, and target population) and the explanatory variable of interest (number of stockout weeks per month). We estimate our model using a random-effects estimator (Generalized Least Squares-GLS), but also include the fixed-effects estimator (Within Group-WG) results in the Appendix to show that our results are robust to the method of estimation.

We built the model incrementally according to the conceptual model. We selected variables carefully to avoid multicollinearity, which interferes in assessing the effects of the variables of interest (i.e., coefficients are unstable). As we built the model, we used Spearman correlation matrices to ensure that none of our explanatory variables are too related to each other (we use a threshold of $R^2 = 0.90$). The correlation matrices for the full model can be found in the Appendix.

Table 2
Description of model variables.

Variable	Description	Source	Level of aggregation	Format
Month_Yr	Date of observation (YYYY-MM-01)	–	–	Date
Month_Num	Sequenced number of month	–	–	Numeric
State	State name	–	–	Factor
LGA	Local Government Area name	–	–	Factor
State_LGA	Unique identifier for each State-LGA pair	–	–	Factor
Vaccine	Name of vaccine	–	–	Factor
num_stockout_weeks	Number of weeks (in each month) where stockouts were reported	Navision	LGA	Integer
num_immunized	Total number of children immunized for each vaccine (all doses), each month (outliers removed)	DVDMT	LGA	Integer
is_campaign	1 if any campaign for a vaccine took place in this month, 0 if no campaigns took place	Campaign working groups	State	Logical
is_upcoming_campaign	1 if any campaign for this vaccine will take place in the next 3 months, 0 if there are no upcoming campaigns	Campaign working groups	State	Logical
access_problem	Percent of women reporting at least one problem accessing health care	NDHS 2013	State	Numeric
diag_accuracy	Average proportion of correct diagnoses provided by clinical staff	NHFS 2016	State	Numeric
mothers_age	Median age at first birth	NDHS 2013	State	Numeric
target_pop	Estimated number of surviving infants born in each LGA, each year, rescaled/1000, year-specific	DVDMT	LGA	Numeric

In some cases, explanatory variables which are not significant were kept in the model because they fit conceptually and might reduce variation. We use a mixed-effects general linear model because our data is a time series (panel) dataset and therefore we need to account for the correlation of observations at the district level (LGA) across time and per month across LGAs.

2.4. Regression equation

The regression equation based on the conceptual model is

$$y_{it} = \alpha + u_i + \mu_t + \gamma z + \beta x_i + \epsilon_{it}$$

where α is the intercept, u_i is a group-specific (LGA-specific) random element, μ_t is a time-specific (month-specific) random element, z is the set of control variables and γ the vector of their effect, x_i denotes the vector of stock availability (the explanatory variable of interest) in the current and in previous months, as measured by the number of weeks of stockouts in a given month in LGA i , β is the vector of regression coefficients of the impact of stockouts, and ϵ_{it} is the error term. The variable y_{it} is the response variable (number of children immunized in LGA i in month t).

3. Results

The model results are shown in Table 3. The asterisks (*) note which variables are significant at the 95% level. Each vaccine's model is estimated separately and the number of observations per cluster can be found in the Appendix. The impact estimates are on the number of children immunized per LGA and per month. For example, a stockout of the yellow fever vaccine reduces the number of children immunized in the same month in each LGA by 76.

4. Discussion

4.1. Do vaccine stockouts affect immunization coverage? If so, how?

Table 4 shows the three ways in which immunization coverage may be affected by stockouts.

Mechanism 1: Direct stockout impact

Our results confirm an intuitive result that across all vaccines, a stockout decreases the number of children immunized today. For example, a stockout of BCG results in 111 fewer children immunized in the same month in an average LGA. This is intuitive, but

our analysis confirms/validates this and demonstrates that the size of the effect is large.

Mechanism 2: Learning effects

When parents/family members of a child observe a stockout at their health facility they may tell others that the facility has no vaccines, which may affect the others' decision to take their children for immunization in future months. In addition, a stockout today leads parents to lose confidence in the health care system, making them less likely to return later to have their child immunized. We term these two dynamics "learning effects." We use the example of measles because it is a single-dose regimen. If there are no learning effects, the number of children immunized against measles in a certain month should not be affected by stockouts in previous months. However, if these effects exist, we would expect stockouts in previous months to affect the number of children immunized in the current month.

Our results show that learning effects are significant for the measles vaccine. A stockout of measles results in 77 fewer children immunized in the current month and 25 fewer children immunized the following month in an average LGA. We see the same effect for most vaccines.¹

The results show that stockouts may have a positive effect on the number of children immunized later due to children "catching-up" with the regimen when a vaccine is back in stock. The magnitude of this increase is always smaller than the initial decrease—more children drop out of the regimen due to a stockout than catch up later. The magnitude of the catch-up varies across vaccines. In general, looking at aggregate data and the average impact over multiple months, we could say that the net impact of a stockout is that about half of the current demand is permanently lost. For example, a stockout of BCG results in 111 fewer children being immunized in the current month, but 13 additional children immunized the following month and 22 additional children immunized three months later. These results hold even for multi-dose regimens such as pentavalent and hepatitis B, despite the confounding effect of multiple doses. A pentavalent stockout,

¹ PCV is a special case. The results show that the previous months' stockouts have significant, negative effects on current immunizations for PCV and that this effect lasts for six months. This may be due in part to learning effects, but it is compounded by the persistent shortages of PCV at the beginning of our dataset. These shortages are confirmed by the correlation matrices (see: Appendix) which show that for PCV, each months' stockouts seem to be slightly correlated with the two adjacent months.

Table 3
Full regression model output. The numbers in parentheses are the standard deviations of each coefficient (the standard error). The asterisks indicate the level of statistical significance.

	Dependent variable: Number of children immunized						
	Polio	BCG	Measles	Yellow Fever	PCV	Penta	Hepatitis B
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Current stockouts	-226.4*** (35.1)	-111.8*** (7.4)	-77.3*** (8.9)	-76.3*** (7.3)	-171.8*** (20.4)	-96.5** (43.7)	-55.9*** (8.2)
Stockouts in prior month	-82.6** (34.8)	13.5* (7.5)	-25.1*** (8.9)	-4.4 (7.7)	-132.8*** (23.5)	77.1* (41.8)	-32.8*** (8.2)
Stockouts 2 months prior	-19.4 (34.2)	1.2 (7.5)	4.9 (8.6)	42.9*** (7.6)	-106.4*** (23.0)	38.0 (36.6)	12.1 (8.0)
Stockouts 3 months prior	-29.5 (34.2)	22.4*** (7.4)	-1.3 (8.3)	-21.5*** (7.5)	-101.0*** (22.5)	-8.3 (35.5)	-16.0** (8.0)
Stockouts 4 months prior	-24.1 (33.2)	14.4* (7.5)	20.4** (8.1)	17.3** (7.6)	10.0 (20.9)	17.5 (34.6)	-8.5 (8.6)
Stockouts 5 months prior	-17.8 (33.0)	12.2* (7.2)	8.2 (7.9)	5.9 (7.4)	-13.8 (20.0)	-27.6 (29.0)	22.3*** (8.4)
Stockouts 6 months prior	-7.0 (40.2)	-2.6 (7.0)	6.2 (7.5)	-8.8 (7.4)	-54.2*** (19.0)	-1.8 (28.7)	11.4 (8.2)
Presence of a campaign	-118.6*** (24.7)		-25.0* (14.4)				
Presence of a campaign 1 month prior	-37.0 (25.3)		-116.4*** (16.2)				
Presence of a campaign 2 months prior	6.0 (24.8)		29.0* (16.0)				
Presence of a campaign 3 months prior	-71.1*** (23.9)		-58.3*** (14.5)				
Presence of a campaign 4 months prior	-12.9 (23.9)						
Presence of a campaign 5 months prior	33.8 (24.3)						
Presence of a campaign 6 months prior	22.2 (22.8)						
Presence of a campaign 7 months prior	52.8** (24.6)						
Presence of a campaign 8 months prior	55.8** (24.8)						
Presence of a campaign 9 months prior	-22.5 (26.3)						
Presence of an upcoming campaign	-93.7*** (31.7)		22.4** (9.1)				
Problems in accessing health care	-1,182.6*** (251.6)	-399.2*** (90.9)	-241.6*** (77.8)	-238.8*** (74.1)	-400.2* (226.0)	-700.5*** (180.4)	-372.3*** (69.6)
Diagnostic accuracy	1,417.3*** (307.0)	425.5*** (110.5)	489.5*** (94.7)	477.3*** (90.2)	140.9 (330.9)	1,224.7*** (219.5)	-62.1 (84.6)
Mother's age	-83.9*** (18.7)	7.5 (6.2)	-24.7*** (5.3)	-22.4*** (5.1)	-29.7* (16.2)	-66.4*** (12.4)	12.1** (4.8)
Target population for immunization	306.8*** (6.7)	88.4*** (2.4)	74.9*** (2.1)	73.5*** (2.0)	226.9*** (9.0)	235.3*** (4.8)	59.3*** (1.9)
Constant	2,273.5*** (482.1)	-17.8 (158.0)	641.4*** (135.6)	580.5*** (129.0)	1,060.3*** (410.2)	1,675.0*** (315.0)	-61.7 (121.5)
Observations	10,774	12,877	12,857	12,870	4,882	12,889	12,768
Log Likelihood	-89,299.4	-91,710.0	-91,640.2	-91,025.4	-38,833.1	-103,723.3	-88,867.3
Akaike Inf. Crit.	178,650.9	183,449.9	183,320.3	182,080.9	77,696.2	207,476.5	177,764.6
Bayesian Inf. Crit.	178,840.3	183,561.9	183,469.5	182,192.8	77,793.6	207,588.5	177,876.4

Note: * p < 0.05, ** p < 0.01, *** p < 0.001.

for example, results in 96 fewer children immunized in the current month, but 77 additional children immunized the following month.

Unfortunately, we cannot determine the extent to which immunization regimens are disrupted because the dose-specific data are not reliable, so we are unable to study the third mechanism (regimen interruption).

In conclusion, we see same pattern across vaccines—stockouts reduce the number of children immunized in the short term, usually for several months. These effects last longer for some vaccines than for others. About half of the initially lost demand is recovered over the following six months as children catch up with the regimen when vaccines are back in stock.

4.2. What factors impact the size of the effect?

Our results show that problems in accessing health care and diagnostic accuracy have a large and significant effect on immunizations. This confirms previous literature [4,5,7,16,26] and health experts' opinions—health care access and the strength of the health system affect routine immunization. Mother's age has a smaller impact on the number of children immunized and the impact is different than in findings from previous literature [6], likely due to the variable we use in our model (the median age at first birth, by state).

Our results also show that campaigns reduce demand for routine immunization in the short term but generate some demand

Table 4
Ways in which vaccine stockouts may impact immunization coverage.

	Mechanism	Finding
1	A stockout today may prevent parents from immunizing their children today (<i>direct stockout impact</i>).	Significant
2	A stockout today may cause parents to tell neighbors and friends that a facility has no vaccines, which may affect their decision to take their children for immunization and may affect the number of children immunized in future months. A stockout today may also cause parents to lose faith in the health care system and may cause them not to return later to have their child immunized. We term these the <i>learning effects</i> .	Significant for most vaccines
3	A stockout today may interrupt an immunization regimen with multiple doses, which may affect the timing of subsequent doses (<i>regimen interruption</i>).	Unable to determine without dose-specific data

for routine immunization in the long term; some parents may delay routine immunization in anticipation of future campaigns (see: Table 3). However, detailed analysis of the impact of campaigns on routine immunization is beyond the scope of this paper.

5. Conclusions

Our findings provide insights for immunization programs in Nigeria and similar settings. The impact of stockouts on the number of children immunized with each vaccine can be read from Table 3. Across all vaccines, we find that:

- Stockouts of vaccines decrease the number of children immunized in the short term, usually for several months.
- When a stockout occurs, about half of the demand is permanently lost. The rest is regained later as children “catch-up” when a vaccine is back in stock.
- Access to and strength of the healthcare system have a significant impact on routine immunization.

Our findings have implications for many routine immunization programs.

We find that the impact of stockouts is significant and lasts longer than the current month. Efforts to reduce the incidence of stockouts through supply chain transformation should continue and should therefore be prioritized. Supply chain transformation efforts focused on the collection of consistent, high-quality supply chain data and on maintaining reliable, readily-released funding streams for the distribution costs of vaccines are critical to reducing vaccine stockouts and consequently, improving immunization coverage.

Supply of vaccines and utilization of immunization services are interrelated—the supply of a vaccine affects the demand for that immunization now *and* in the future. The supply of and demand for immunization should be considered holistically when designing vaccine programs.

6. Limitations

Our effort has several limitations which can be addressed with future research. First, due to data limitations we use a service level stock availability indicator. There is some anecdotal evidence that when clinics have less inventory they engage in prioritization, waiting to open vials, etc. Future work can use data on amount of inventory (fill rate metrics) to evaluate the impact of increased inventory on immunization coverage. Second, this study uses weekly availability data at the LGA level and not at each immunization service delivery point. Future work in countries where stock systems capture clinic-level vaccine stock and use data can investigate the impact of vaccine availability on regimen completion and cross-antigen stockout effects. Third, while this paper quantifies the aggregate effects, future research should investigate geographic effects within and across LGAs including controlling for population migration in areas with large migratory populations or

adjacent/contiguous state/LGA boundaries. The primary focus of our study is only on one driver of immunization coverage—supply of vaccines—but other drivers exist and should continue to be explored. Finally, this study is based on Nigeria and we cannot comment definitively on the external validity of these findings. The findings would not apply to other developing regions where supply chain structure, financing and health system design are very different from what is observed in Nigeria. Future work should carry out such analysis in other and multiple countries using more comprehensive and more granular supply and demand data.

7. Authorship

EG and PY conceptualized the study and ES developed the empirical estimation methodology. EG collected the data, and together with ES and PY analyzed and interpreted it. EG compiled a manuscript and all authors provided critical review and approved the final version.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.vaccine.2019.06.006>.

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