Health System Resilience During a Health Crisis:

The Impact of the COVID-19 Pandemic on Routine Child Immunization in Ghana

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Abstract

To investigate the impact of the COVID-19 pandemic on routine child immunization in a lower-middle-income country, this study uses monthly administrative data from January 2018 to December 2021 across all 260 Ghanaian districts. We analyze the number of children immunized with 15 recommended child vaccines during this time. The detailed data makes it possible to control for seasonal trends and analyze potential catch-up effects 21 months into the pandemic. Given variations in social-distancing regulations across districts, it is possible to further differentiate between the effect of a lockdown and the effect of the pandemic. We find that the fear of COVID-19 and delayed vaccination and outreach campaigns had a substantial negative impact in Ghana. In April 2020, administered vaccines decreased by -9%. However, the disruption started to recover two months later. The reduction in immunizations were larger in lockdown-affected districts and took longer to recover. Nevertheless, these results indicate that the negative effect on yearly child immunization was less severe and shorter lived than predicted by experts. We developed an online dashboard with results on district level to assist policymakers to target the most vulnerable children with supportive policies.

Keywords: COVID-19; vaccines; child immunization; administrative data; Ghana

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1. Introduction

Routine immunizations against childhood illnesses, such as polio, are an essential component of basic health services. Over the last several decades, routine child immunizations have contributed to decreasing the number of vaccine-preventable illnesses and deaths (Andre et al, 2008; Li et al., 2019; Ozawa et al., 2012, World Bank, 2021). Despite this progress, ensuring that every child has access to basic immunization services remains challenging in many low- and middle-income countries (LMICs; Bangura et al., 2020; Chopra et al., 2020, WHO, 2018a). During the COVID-19 pandemic, universal child immunization became even more challenging.

To investigate the impact of the COVID-19 pandemic on essential health services, the World Health Organization (WHO) conducted a survey with health ministries from more than 100 countries between May and July 2020. They found that nearly all countries reported disruptions in basic health services, particularly low- and middle-income countries (LMICs; WHO, 2020a). Routine child immunizations were reportedly among the most frequently disrupted services. Similarly, a cross-country study of ten countries shows that child immunizations, in particular, were disrupted (Arsenault et al., 2022). The reasons for the disruptions include a mix of supply- and demand-side factors. Supply-side factors include logistical barriers, such as the supply of medicines, shifting resources to mitigate the impact of the COVID-19 pandemic, staff shortages, delays of outreach and vaccination campaigns, and the closure of health facilities (WHO, 2020a). On the demand side, disruptions were linked to fear of COVID-19, difficulties in traveling due to physical-distancing regulations, and inability to afford health-care services (Alsuhaibani and Alaqeel, 2020; Chandir et al., 2020a, 2020b; WHO, 2018a, 2020a, 2020b).

These disruptions resulted in major public health concerns (Clark et al., 2020; Roberton et al., 2020; Roberts, 2020), particularly for LMICs (Chandir et al., 2020a, 2020b; Abbas et al., 2020; Rabbani et al., 2021). Disrupting routine child immunization services can lead to an increase in vaccine-preventable diseases such as diphtheria, measles, or polio (WHO, 2020c; 2020d). Abbas et al. (2020) even predicted that not maintaining routine child immunizations in Africa would lead to more childhood deaths than COVID-19. In addition, Roberton et al. (2020) simulated COVID-19's potential effects of essential maternal and child-health services and access to food in 118 LMICs on the mortality rate of mothers and children under five and found a dramatic number of excess deaths (between 9-45% in under-five child deaths and an 8-39% increase in maternal deaths per month).

Firstly, to our knowledge, only a few studies have analyzed the impact of the COVID-19 pandemic on child routine immunization for an entire country with administrative data, especially for LMICs (e.g., Lassi et al., 2020). Arsenault et al. (2022) show in their analysis at the regional level in eight LMICs and two high-income countries (HICs) that there was a substantial disruption of child immunizations in the beginning of the pandemic. The effects, however, varied considerably by country and by region. Thus, cross-country comparisons should be made with care and results from small areas cannot be generalized to the entire country. Our study shows the full extent of the impact of COVID-19 on child immunization and highlights inter-regional differences, by providing evidence for an entire LMIC, namely Ghana, at the district level.

Secondly, most studies only provide evidence of the impact on child immunizations during the lockdown or shortly after the lockdown has been lifted (e.g., Lassi et al., 2020; Chandir et al., 2020a, 2020b; 2020; Rabbani et al., 2021), while only one study analyzes a longer-term impact of 15 months into the pandemic covering Ethiopia, Laos, Mexico, and South Africa (Arsenault et al., 2022). In the longer-term, they estimate that catch-up campaigns have not reached all children. We provide evidence of a long-term impact of 21 months into the pandemic and highlight whether the number of routine child immunizations has recovered and illustrate how a different health system reacts to the additional and more severe COVID-19 waves in 2021.

Thirdly, to our knowledge, only one study from Sierra Leone analyzes all recommended children vaccine types separately, not just the aggregated vaccination coverage rate or a few single vaccine types (Buosenso, 2020). However, this study only provides insights for one single area of Sierra Leone and only for March 2020 and April 2020. Since large differences across vaccine types exist and we provide evidence for all 15 recommended child vaccine types separately, our study improves the understanding of how disruption differed among vaccine types during the COVID-19 pandemic.

Lastly, as many studies conclude, it is difficult to disentangle the potential reasons for vaccination disruptions. On a country level, the stringency of policies or the COVID-19 incidence is only moderately correlated with health-service disruptions (Arsenault et al., 2022). Our study provides evidence on how the overall COVID-19 pandemic and how governmental policies, such as lockdowns, have each impacted the routine child immunizations and contributes to a better understanding of the reasons, which will create important insights about health system resilience.

To fill these gaps and to study the impact of the COVID-19 pandemic on routine child immunization services for one middle-income country in Africa, we analyze administrative data from all 260 Ghanaian districts on all 15 recommended child vaccines from January 2018 to December 2021. Using this extensive data allows us to analyze the impact of the pandemic on routine child immunizations for a entire country, and explore inter-district differences. We are not only able to focus on effects during the lockdown in April 2020 but we can explore potential long-term catch-up effects up to 21 months into the pandemic. We provide aggregated and individual evidence for each of the 15 recommended child vaccines. In addition, since Ghana introduced a public lockdown in only 40 out of 260 districts, Ghana provides a unique case to explore the impact of the lockdown as a mitigation response to the COVID-19 pandemic on immunization services in comparison to the general effects of the pandemic.

We find that the administration of routine child vaccinations in Ghana dropped substantially by 9% during the public lockdown in April 2020. Interestingly, the vaccination rates already decreased in the months before the public lockdown, when the pandemic was already spreading globally but had not reached Ghana. However, immunization services caught-up in 2020 and, on average, we do not find any significant decrease in yearly routine child immunization between 2019 and 2020. In 2021, vaccinations recovered to a normal pre-pandemic growth level. This trend is not influenced by the monthly number of COVID-19 cases, which was still increasing in 2020 and 2021 in Ghana. Nevertheless, we find a substantially larger disruption in April 2020 and a slower recovery until 2021 in lockdown-affected districts. Our results indicate that the fear of COVID-19, and delayed vaccination and outreach campaigns had a substantial impact on routine child immunization services in Ghana.

On a national level, Ghana caught up much quicker with regard to routine vaccinations than predicted by health experts. Given the large spatial variations in the impact of COVID-19 on vaccinations and the differences in impact across vaccines during the COVID-19 pandemic, it is important to not only monitor vaccine disruptions on national level but also on regional and district levels. With the newly created and freely available online dashboard (https://nadel.shinyapps.io/Immunization_Dashboard), we support policymakers in Ghana to gain a better understanding and target the most vulnerable population with supportive policies.

2. Data and Methods

2.1 Context

In comparison to other African countries, Ghana has been hit relatively hard by the COVID-19 pandemic[1]. The first three cases in Ghana were reported on March 14, 2020 (Figure A.1; Hasell et al., 2020). To reduce the spread of COVID-19, on March 15, 2020 the Ghanaian government banned all public gatherings such as conferences, festivals, political rallies, and church activities and closed schools (Figure A.2; Nyabor et al., 2020). In order to avoid an escalation in the number of cases, on March 30, 2020 the government also introduced a geographically concentrated public lockdown in 40 of the most affected districts in the Greater Accra metropolitan area and Greater Kumasi metropolitan area (Figure A.3; Republic of Ghana, 2021a). The lockdown banned all non-essential movement, work, and services. Inter-city movement of vehicles and aircraft for private or commercial purposes was forbidden (Republic of Ghana, 2021b). Essential health services, such as routine child immunizations, were still provided, however, people living in a lockdown area were not allowed to travel to other districts for these services. The geographically concentrated public lockdown was lifted on April 19, 2020, while the social distancing and hygienic regulations, such as capacity limitations for events and church services or wearing face masks, remained in effect (Figure A.2; Haider et al. 2020).

After the lockdown was lifted in April 2020, COVID-19 cases in Ghana were still increasing up to around 1,500 new confirmed cases per day until August 2020 (Figure A.1). Between August and December 2020, the daily number of new confirmed cases dropped considerably, remaining on a relatively low level of around 150 cases. However, starting in December 2020, the number of cases increased again, resulting in a second wave in January 2021 (approximately 1,500 new confirmed cases

[1] Note that testing rates are different between countries, potentially influencing the number of confirmed cases.

per day), a third wave in August 2021 (approximately 2,000 new confirmed cases per day), and a fourth wave in January 2022 (approximately 2,500 new confirmed cases per day; Johns Hopkins, 2021).

2.2 Routine Child Immunization Data

We use time-series data from the District Health Information Management System (DHIMS) provided by the Ghana Health Service (GHS) on 15 vaccination types aggregated by month from January 2018 to December 2021. The monthly values for each vaccination type are available for all 16 regions and 260 districts in Ghana. All indicators measure the number of children (below five years) receiving vaccinations within a given month administered in all health facilities throughout the country. We analyze the vaccinations recommended by the GHS: Measles Rubella 1, Measles Rubella 2, OPV/Polio 0, OPV/Polio 1, OPV/Polio 2, OPV/Polio 3, PCV 1, PCV 2, PCV 3, Penta 1, Penta 2, Penta 3, Rotavirus 1, Rotavirus 2, and Yellow Fever. Although we cannot control for whether the vaccination was given at the recommended time or in the recommended interval, we can investigate the total number of doses given in each district over the 48 months between 2018 and 2021. We do not have information on the number of immunizations planned by each district in a given month. However, we assume that the number of vaccinations should grow similar to the yearly population growth rate of children below the age of five. Due to the of lack of data, we assume the same population growth rate for all districts, which was 1.1% annually between 2018 and 2019 (WHO, 2020e).

In addition, we use four other datasets to create the following variables: a lockdown and COVID-19 impact status variable, a regional COVID-19 cases variable, and district control variables (monthly number of births, population density in 2020, and poverty rate in 2015). Data on the monthly regional number of COVID-19 cases, COVID-19 cases on district level in April 2020, as well as data on public lockdowns in districts in April 2020 are retrieved from Ghana's outbreak response management updates (GHS, 2022). The monthly number of births from January 2018 to December 2021 at the district level is extracted from the DHIMS. The estimated population density at the district level for 2020 is from the Ghana COVID-19 monitoring dashboard (Ghana Health Service, 2022). The poverty rates at the district level are extracted from the Ghana Poverty Mapping Report 2015 (Ghana Statistical Service, 2015). A more detailed description of the data can be found in Appendix S1 and S2.

2.3 Statistical Analysis

In our analysis, we have a balanced sample with 48 time periods (number of months 2018-2021) and 260 districts in Ghana. Our main outcome variable is the total number of routine child immunizations ($Y_{i,m,t}$) for a district (i), month (m), and year (t), adjusted by a yearly population growth rate of 1.1%.[2] Due to strong seasonal variation in vaccination rates, for example, due to birth rates or distribution campaigns, we compare only the number of immunizations for the same month over the years or the total yearly changes. This approach is in line with other studies that compare vaccination rates (Bramer et al., 2020; MacDonald et al., 2020; Buonsenso, 2020).

In a first step, in Section 3.1, we explore the overall impact of the COVID-19 pandemic on routine child immunization by analyzing the yearly growth rate of the number of total doses per district from April 2019 to April 2020 as well as from 2019 to 2020 and from 2019 to 2021. The yearly growth rate per district from 2018 to 2019 will serve as a control to understand pre-pandemic patterns. Equation (1) shows, how we calculate the growth rate from 2019 to 2020:

$$(1) \qquad \sum_{i=1}^{260} \frac{\sum_{m=1}^{12} Y_{i,m,2020} - (\sum_{m=1}^{12} Y_{i,m,2019} * 1.011)}{\sum_{m=1}^{12} Y_{i,m,2019} * 1.011}$$

In a second step, in Section 3.2, we analyze the development of routine child immunization by month based on the following OLS regression model with month fixed effects ($Month_{i,t}$), year fixed effects ($Year_{i,m}$), district control variables ($D_{i,m,t}$), and regional COVID-19 cases ($\beta_5 C_{i,m,t}$). Additionally, we include the average number of vaccinations in 2018 and 2019 to control for differences in levels of vaccinations administration (T_i). We introduce the control variables with a stepwise approach to test their effect on the coefficients and we use cluster-robust standard errors on a regional level. Our coefficient of interest is the interaction term ($Month_{i,t} * Year_{i,m}$) and is shown in the table in Section 3.2.

$$(2) \qquad Y_{i,m,t} = \beta_0 + \beta_1 Month_{i,t} + \beta_2 Year_{i,m} + \beta_3 Month_{i,t} * Year_{i,m} + \beta_4 D_{i,m,t} + \beta_5 C_{i,m,t} + \beta_6 T_i + \varepsilon_i$$

[2] This means that for a nominal change in the number of vaccinations of 1.1%, the calculated real growth rate over time of vaccinations would be 0%.

In a third step, in Section 3.3, we disentangle the effects in lockdown- and non lockdown-affected districts. Therefore, we create a five-level lockdown and COVID-19 impact status variable (I_i)[3] to indicate if the district was affected by COVID-19 cases at the beginning of the pandemic and how far the district was away from the geographically concentrated public lockdown in April 2020 (for more details, see S2 in the Appendix). For districts very close to the lockdown-affected districts (neighbor districts), we assume that they are very similar in terms of the fear of COVID-19 exposure[4], but different in terms of restrictions. Additionally, we also control for district control variables ($D_{i,m,t}$). Our coefficient of interest is the interaction term ($I_i * Year_{i,m}$) and is shown in the table in Section 3.3.

(3) $$Y_{i,m,t} = \beta_0 + \beta_1 Month_{i,t} + \beta_2 Year_{i,m} + \beta_3 I_i + \beta_4 I_i * Year_{i,m} + \beta_5 D_{i,m,t} + \beta_6 T_i + \varepsilon_i$$

In a final step, in Section 3.4, we analyze the development of routine child immunization by vaccine type using again equation (1), but we run the analysis for each of the 15 vaccine types individually.

Additionally, we conduct a series of sensitivity analyses (results available from authors upon request). First, we run equation (2) for each of the 15 vaccine types individually to understand if they follow the same trend as the total number of vaccinations. Second, in equation (3), we use a three-level lockdown impact status variable (lockdown-affected districts, neighbor districts, other districts) instead of the lockdown and COVID-19 impact status variable to see if the results are robust without the COVID-19 cases information. Third, we run equations (2) and (3) with different specifications of (T_i), such as the average number of vaccinations from 2018, the average number of vaccinations from 2019, and the lagged number of vaccinations one period before. Lastly, we run all results for non-population growth adjusted numbers[5].

[3] (I) lockdown-affected districts with COVID-19 cases, (II) neighbor districts of lockdown-affected districts with COVID-19 cases, (III) neighbor districts of lockdown-affected districts without COVID-19 cases, (IV) districts that are further away than neigbors with COVID-19 cases, (V) districts that are further away than neigbors without COVID-19 cases

[4] COVID-19 cases were published only at regional level, so people in each districts did not know how much their district was affected (GHS, 2022)

[5] The results without population growth adjusted numbers lead to the overall same patterns and significance levels of the results, but scaled to a marginally more positive trend. Therefore, our estimates are rather conservative.

3. Results

3.1 Development of routine child immunization by month

In April 2020, when the first COVID-19 cases were recorded in Ghana and a public lockdown was implemented in 40 out of 260 districts (Figure A.3), we find that, on average, child immunizations significantly decreased by -557 doses (95% CI: -754 – -360 doses) per district or -6.4% (95% CI: -8.8% – -4.1%) relative to April 2019 across the country. However, we find a large variance across districts, ranging from a decrease of -88% in Ablekuma Central (Greater Accra Region) to an increase of +82% in Mamprugu-Moagduri (North East Region) of vaccination doses administered between April 2019 and April 2020 (Figure 1a). In 138 districts, the number of immunizations dropped, in 67 it stayed about the same (-5% – +5%), and in 55 it increased.

However, comparing the total yearly number of doses administered in 2020 with 2019 (Figure 1b) indicates that, on average, immunizations decreased only by -1.2% (95% CI: -2.4% – +0.3%) across districts. Hence, immunization rates largely recovered after the severe drop in April 2020, even when COVID-19 cases were rising all over the country. Between 2019 and 2020 and across districts, in 85 districts the number of immunizations dropped, in 109 it stayed about the same (-5% – +5%), and in 66 it increased. The observed changes range from less than -38% in Ayawaso Central (Greater Accra Region) to + 31% in Bolgatanga East (Upper East Region).

Figure 1c further shows that before the COVID-19 pandemic, the yearly number of routine child immunization doses administered significantly increased from 2018 to 2019 by +1.9% (95% CI: +0.3% – +3.5%) per district. However, even before the pandemic, we observe a range in the growth rate of vaccination administered from -40% in a district in Volta Region up to more than +60% in some districts in Greater Accra Region. Hence, an analysis of the impact of a shock on immunization rates in a single district might be highly misleading, as even in non-pandemic years immunization rates vary quite substantially from one year to the other within certain districts, whereas on the country level they may remain constant or slowly increase.

Comparing the pre-pandemic level with the level in 2021 shows that, on average, the total number of doses administered between 2019 and 2021 (Figure 1d) significantly increased by +4.2% (95% CI:

+2.4% – +6.1%) per district over the two years. This highlights that the growth rate between 2020 and 2021 was substantially larger than the average +1.9% pre-pandemic growth rate: from 2020 to 2021 the total yearly number of doses administered increased by +5.4% (95% CI: +4.1% – +6.7%) per district. This finding indicates that at the national level, the number of doses administered has fully recovered even during a second and third COVID-19 wave (Figure A.1). Nevertheless, 28 districts still show a negative development of more than -5% from 2019 to 2021, indicating that not all districts have fully recovered.

The results highlight that the administration of routine child vaccinations in Ghana caught up much quicker than assumed by health experts. We find large spatial variations in the impact of COVID-19 on vaccinations, emphasizing the importance to not only monitor national but also regional and district trends in disruptions of vaccinations. All results on district level can be found in the newly created and freely available online dashboard (https://nadel.shinyapps.io/Immunization_Dashboard).

3.2 Impact of the COVID-19 pandemic on routine child immunization

Figure 2 shows the change in monthly doses administered. It highlights that although there was a substantial drop in the number of total doses during the public lockdown in April 2020, the numbers seem to recover already two months afterward and are higher in June to August 2020 than in June and July 2019 before the pandemic, but not on a significant level. September to December 2020 follow a similar trend to the previous years (2018 and 2019). The numbers in 2021 again follow the overall seasonal trend of immunization over the year but are substantially higher than in 2018 or 2019. This seasonal trend highlights that comparing the number of doses from one month to the next within the same year might be highly misleading. We, therefore, only compare monthly or yearly doses from one year to another. Interestingly, Figure 2 also shows that there was already a decrease in administered doses before COVID-19 first occurred in Ghana in March 2020 and before the public lockdown in April 2020, indicating that the public lockdown only partially explains the severe drop in child immunizations.

Table 1 formally analyzes the monthly differences in number of vaccinations between 2019 and 2020 based on an OLS regression model (Section 2.3, equation 2). In Table 1 column 2, we find a significant drop even before the first COVID-19 case in Ghana occurred and before the public lockdown was implemented: -217 fewer doses (about -4 p.p.) in February 2020 (relative to February 2019) and -365 fewer doses (about -7 p.p.) in March 2020 (relative to March 2019). When the public lockdown was in place, we observe a significant decrease of on average -493 total doses (about -9 p.p.) per district from April 2019 to April 2020. The effects also do not substantially change if we control for district characteristics as well as regional COVID-19 cases (Table 1, columns 1 and 2). Small statistically significant recovery effects can be found already in June (+379 more doses, about +7 p.p., relative to June 2019) and December (+222 more doses, about +4 p.p. relative to December 2019). In 2021, the month and year interaction terms show a significant recovery relative to 2019 for almost all months.

The results again highlight a much faster and stronger recovery of routine child immunizations than the literature has previously predicted. Additionally, the results emphasize that the fear of COVID-19 before it even first occurred in Ghana already impacted people's behavior. Interestingly, the monthly number of COVID-19 cases seem not to impact people's behavior.

3.3 Impact of the public lockdown on routine child immunization

We find a large difference in the effects between the 40 lockdown-affected districts and the districts that did not experience a public lockdown (220 districts): in lockdown-affected districts, the total doses per district from April 2019 to April 2020 decreased on average by 1,361 doses (about -14 p.p.) and in not-affected districts by 360 doses (about -8 p.p.; see Table A.1 in the Appendix). Table 2 (column 5) shows based on an OLS regression model (Section 2.3, equation 3) that this difference is statistically significant, independent of whether non lockdown-affected districts had COVID-19 cases or whether they were close to districts with a lockdown (neighbor districts). Additionally, we find that districts further away from those with a lockdown have a significantly lower drop as well as non lockdown-affected districts without COVID-19 cases have a significantly smaller drop than non lockdown-affected districts with COVID-19 cases and the lockdown-affected districts[6].

[6] However, districts further away from the lockdown-affected districts (other districts) seem to be already influenced in 2018 by factors we cannot control for (see Table 2, e.g., column 3). Therefore, for the rest of the analysis, we focus only on the difference between lockdown-affected districts and neighbor districts.

In January 2020, when China reported the first death from COVID-19, but the pandemic had not yet spread globally, we do not find any significant difference between lockdown-affected districts and their neighbors (Table 2, column 2). However, in February 2020, when the first death from COVID-19 outside of China was reported and Italy had a major surge in cases, we already find a significant difference between the district types (Table 2, column 3). Similar, in March 2020, when the first COVID-19 case occurred in Ghana and the president started with weekly updates on measures taken against the spread of COVID-19, but before the public lockdown was in place, we again find a significant difference between the district types (Table 2, column 4). Neighbor districts without COVID-19 cases had a 1,334 doses and neighbor districts with COVID-19 cases a 1,230 doses lower drop relative to lockdown-affected districts in March 2020 (relative to March 2019). After the lockdown in April 2020, from May to December 2020 (relative to May to December 2019), neighbor districts without COVID-19 cases had a substantially lower drop of 453 doses than lockdown-affected districts, whereas for neighbor districts with COVID-19 cases, we do not see any significant differences (Table 2, column 6).

Over the period of a year, the statistically significant differences between lockdown- and non lockdown-affected districts remain (Table 2, column 1). This indicates that the 56 districts with a negative yearly development from 2019 to 2020 (see Section 3.1) seem to be concentrated in lockdown and COVID impacted districts. Nevertheless, in 2021 relative to 2019, lockdown- and non lockdown-affected districts are not significantly different from each other over a one-year period (Table 2).

The results highlight that first the fear of COVID-19 (prior to the lockdown), but then also the governmental lockdown had a substantial impact on routine child immunization services in Ghana. Additionally, lockdown-affected districts need longer to recover from the COVID-19 shock and take until 2021 to get to a normal pre-pandemic level. Again, we find that this trend is not influenced by the monthly number of COVID-19 cases.

3.4 Heterogeneous effects by vaccine type

Similar to the development of total doses discussed in Section 3.1, several of the 15 different vaccination types show a substantial drop from April 2019 to April 2020, such as -22.2% (95% CI: -37.5% – -6.8%) for Yellow Fever, -6.1% (95% CI: -11.4% – -0.9%) for OPV Polio 2, -5.6% (95% CI:

-10.8% – -0.3%) for Rotavirus 2, and -5.5% (95% CI: -11.0% – -0.0%) for PCV 2 (Figure 3, upper left panel). For time-critical vaccines, such as Polio 0, we do not find statistically significant changes from April 2019 to April 2020.

However, again similar to the development of total doses, studying each of the 15 vaccination types reveals that the yearly development from 2019 to 2020 is not different from zero (Figure 3, upper right panel). It ranges from a drop of -2.5% (95% CI: -5.8% – 0.8%) for Measles Rubella 2 or -2.3% (95% CI: -5.7% – 1.1%) for Yellow Fever up to even a positive development for Penta 1, Penta 2, and PCV 3 of around +0.1% (95% CI: -2.6% – 2.7%).

From 2019 to 2021, we see a statistically significant positive development of around 4% for almost all vaccine types (Figure 3, lower right panel). Exceptions are Measles Rubella 2 with +0.5% (95% CI: -2.7% – 3.6%), Measles Rubella 1 with +1.9% (95% CI: -1.3% – 5.2%), and Yellow Fever with -2.4% (95% CI: -1.6% – 6.0%) – all not statistically different from zero.

The results highlight that the reasons for vaccination disruptions mentioned in the literature, such as closed health facilities or shortages in vaccines and personal protection equipment , seem not to be the main driver in Ghana, since Polio 0, which is given at birth in health facilities, seems uninterrupted. On the contrary, delayed vaccination campaigns – as was the case for yellow fever (Gavi, 2020b; WHO, 2020e) – seem to play an important role. Nevertheless, all vaccine types recovered over the course of a year.

4. Discussion and Conclusion

This study is one of the first investigating the long-term development of routine child immunization for an African country two years into the COVID-19 pandemic. Our extensive dataset - including monthly number of doses for 15 vaccinations per district for the years 2018 to 2021 in Ghana - allowed us to compare the number of vaccines administered,while taking into account seasonal trends, and estimating the effect before, during, and after a lockdown per district. Additionally, the geographically concentrated public lockdown Ghana implemented provides a unique opportunity to compare districts that had lockdowns with other districts within one county.

During the public lockdown in Ghana, we find that the disruption in the administration of routine child vaccinations at country level was much lower than predicted by health experts (e.g., Roberton et al., 2020; Abbas et al., 2020). In our fixed effect OLS regression, we show that during the public lockdown, in April 2020, the total number of child routine immunizations doses decreased significantly by -9% (compared to April 2019) across Ghana. This result is substantially lower than studies found in selected areas of a country, for example reductions of -80% in Karachi, Pakistan (Chandir et al., 2020b) and -84% in one hospital in Sierra Leona (Buonsenso, 2020). However, we also find large spatial variations in the impact of COVID-19 on vaccinations during the lockdown. If we only focus on the areas with the highest reported COVID-19 cases and highest population density districts in Ghana, we also find a very large decrease of over 80% in April 2020 – but not across all districts. This result emphasizes the need for country-wide data, instead of analyzing only some provinces, in order to fully understand the effect of COVID-19.

Few months after the lockdown, in June 2020 and December 2020, we find significant recovery effects. Overall, the yearly number of doses administered in 2020 were similar to 2019 . From 2020 to 2021, the number of doses even significantly increased by 5.4%, fully recovering to a pre-pandemic trend. This is a substantially faster catch-up effect than expected by health experts (e.g., Roberton et al., 2020; Abbas et al., 2020), especially since COVID-19 cases were still increasing. Our findings contribute to the study from Arsenault et al. (2022), who showed that immunization level recovered substantially six months into the pandemic for four LMICs. However, 15 months into the pandemic the catch-up effect still has not yet reached all children.

Additionally, based on our extensive dataset accounting for seasonal trends, we find that the drop in routine child vaccinations started in February and March 2020, even before the first COVID-19 case occurred in Ghana, and before the implementation of social distancing and public-lockdown measures. This is contrary to one study in Bangladesh that also covers pre-pandemic months and accounts for seasonal trends in a LMIC, who do not find any pre-pandemic drops in immunizations (Rabbani 2020). Future studies are needed to investigate if the case of Ghana is rather exceptional.

We provide evidence that the monthly number of COVID-19 cases is not substantially correlated with the administration of routine child vaccination. This finding is in line with our identified catch-up effect until 2021 despite rising COVID-19 cases and more severe COVID-19 waves. Similarly to the study from Arsenault et al. (2022), who show on country-level that the stringency of policies or the COVID-19 incidence are not significantly correlated with health service disruptions.

We find that on average the 40 lockdown-affected districts compared to the districts that did not experience a public lockdown but also had COVID-19 cases need longer to recover from the COVID-19 shock and to reach a normal pre-pandemic level. Nevertheless, some lockdown-affected areas did not show a decrease in vaccination rates even in April 2020, revealing that even within the same country and with the same restrictions the effect of a lockdown can vary a lot. This finding is in line with the results from Rabbani (2020), who found that higher COVID-19 exposure early in the pandemic significantly worsens immunization disruptions for Bangladesh. It also contributes to Arsenault et al. (2022) findings that metropolitan regions had larger disruptions. We identify some highly impacted areas independent from the lockdown, giving policymakers insights on where additional policies or campaigns might be required to target unvaccinated or under-vaccinated children (https://nadel.shinyapps.io/Immunization_Dashboard).

Moreover, we find large variations among the 15 recommended child routine vaccines. We witnessed the largest disruption for yellow fever vaccinations, whereas for time-critical vaccinations that are given at birth (Polio 0), we do not find any significant disruptions — even in lockdown-affected areas in April 2020. This is contrary to studies from other countries that found disruption in time-critical vaccinations given at birth (Buonsenso, 2020; Arsenault et al., 2022; Rabbani, 2021). The variation in results again highlight the need for more country-wide studies for all recommended routine child vaccination in order to fully understand the effects.

In general, the findings suggest that limited access to health facilities due to closed facilities or traveling restrictions was not a driving factor of the disruptions since time-critical vaccinations as well as the number of patients who had to come to the health facility to give birth was not interrupted. Moreover, the disruptions in lockdown-affected districts occurred already in February and March 2020

– before the actual lockdown was implemented – and lasted until after lockdowns were lifted, which emphasize that travel barriers were not a significant cause. Another reason for the disruptions, mentioned in the literature, is that people cannot afford the health service anymore, due to the worsened economic situation (WHO, 2018a). However, we argue that this does not apply to our case, since all routine child vaccinations are given out for free in Ghana. Additionally, we do not find a significant correlation between wealth and the level of disruption in our results, which indicates that an inability to afford travel costs to the health facility was not a main driver. Moreover, we do not find a country wide shortage of vaccines causing disruptions.

Reasons more likely to drive the disruption in routine child immunizations in Ghana, are due to increased concerns of people visiting a health facility for non time-critical vaccines, and delays in vaccination campaigns and outreach sessions of community health workers early in the pandemic. The disruption of vaccinations in February and March 2020 - which started before the first case of COVID-19 was reported in Ghana, but when pandemic was already widely featured in Ghanaian media - indicate that people were concerned of potential infection when visiting a health facility, and postponed it if not absolutely necessary. Disruptions of national vaccination campaigns in the beginning of the pandemic might have also driven short-term disruptions. In particular, the decrease in yellow fever vaccinations in April 2020 could have been due to the national yellow fever campaign that was scheduled in April 2020 but had to be postponed to November 2020 (Gavi, 2020b; WHO, 2020e). Additionally, disruptions of some local outreach programs could potentially also lead to short-term disruptions. An interview with a community nurse in a lockdown-affected district in Greater Accra emphasized this problem. She describes that in the short-term, community nurses were not able to sustain their outreach and had shortages in personal protective equipment(WHO, 2020f). Nevertheless, a few weeks after the initial "lockdown shock," health workers were able to adapt and resumed outreach services, even with rising COVID-19 cases. Since many patients were still afraid of getting infected with COVID-19, more health workers visited patients at home and a new policy also encouraged outreach and home visits for child vaccinations (Arsenault et al., 2022). However, due to the limited data we cannot completely disentangle the effects of these three potential sources. Nevertheless, our results are in line with Arsenault et al.

(2022), who found the decrease in April 2020 in ten different countries was not caused by an overburdened health system but rather a combination of demand-side effects and policy responses.

Two other limitations of the study are that we cannot perfectly control for under-five population growth per district but assume a constant growth rate and that our results cannot be generalized for other country contexts. For population growth, we also run the results without adjusting for population growth, resulting in the same overall patterns and significance levels of the results, but scaled to a marginally more positive trend. Additionally, in the models we control for birth rates per district. Therefore, our estimates are rather conservative. Although results from one country cannot be generalized for other counties, which has been already highlighted in several comparison studies (e.g., Lassi et al., 2021; Arsenault et al., 2022), most studies in LMICs show a substantial drop in April or May 2020 for most of the vaccines (Arsenault et al., 2022).

Future studies that investigate the long-term and country-wide impact of COVID-19 on routine child immunization will show if the positive catch-up effects seen in most districts in Ghana is rather exceptional or if predictions and models have underestimated the reaction time of the healthcare system. Thus, it seems essential to further investigate the impact and understand the reasons behind the trends in order to quickly react and allocate resources to the districts that most need it. Additionally, more studies with a complete yearly dataset are needed in order to compare the overall effect, especially since many countries experience new and sometimes much stronger COVID-19 waves.

Tables and Figures

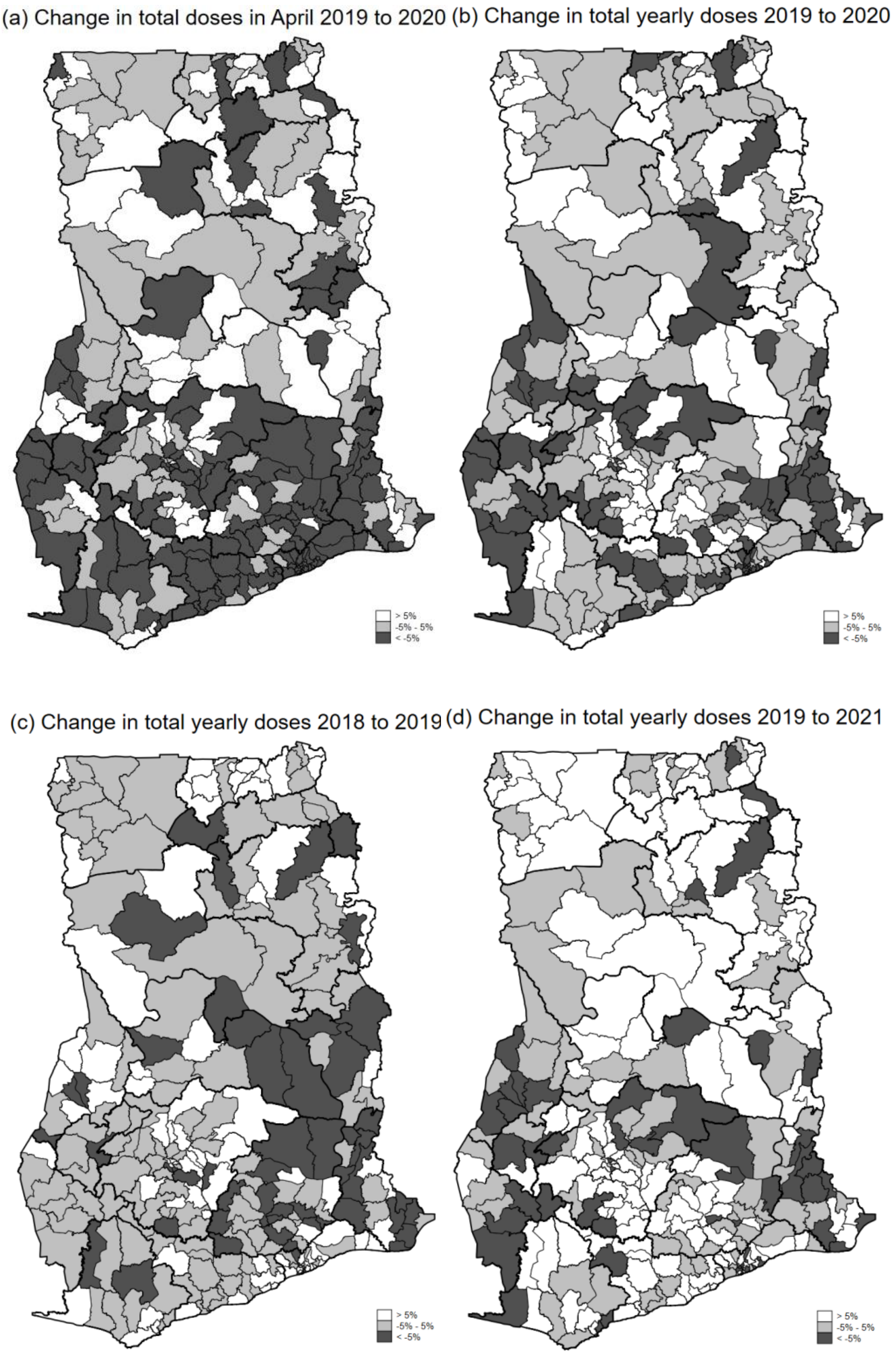


Figure 1: Differences of routine child immunization total doses

Note: Figure (a) shows the difference of total number of administered doses of all children routine vaccines per district for April 2020 compared to April 2019. Figure (b) shows the yearly total change from the number of doses from 2019 to 2020. Figures (c) and (d) show the yearly total change from the number of doses from 2018 to 2019 and 2019 to 2021, respectively. All results are population growth adjusted. Detailed results per districts and for each immunization type can be found in the online dashboard: https://nadel.shinyapps.io/Immunization_Dashboard/

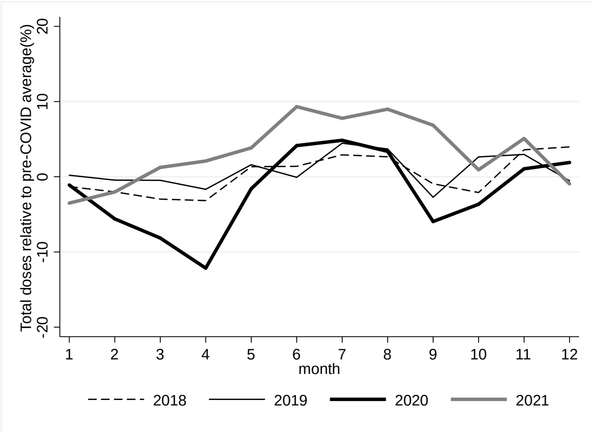


Figure 2: Development of total routine child immunization doses by month
Note: The figure shows the monthly average development of total doses of the vaccinations for the year 2018, 2019, 2020, and 2021 relative to pre-COVID average (2018 and 2019). All results are population growth adjusted. The OLS model analyzing the monthly differences between the years can be found in Table 1.

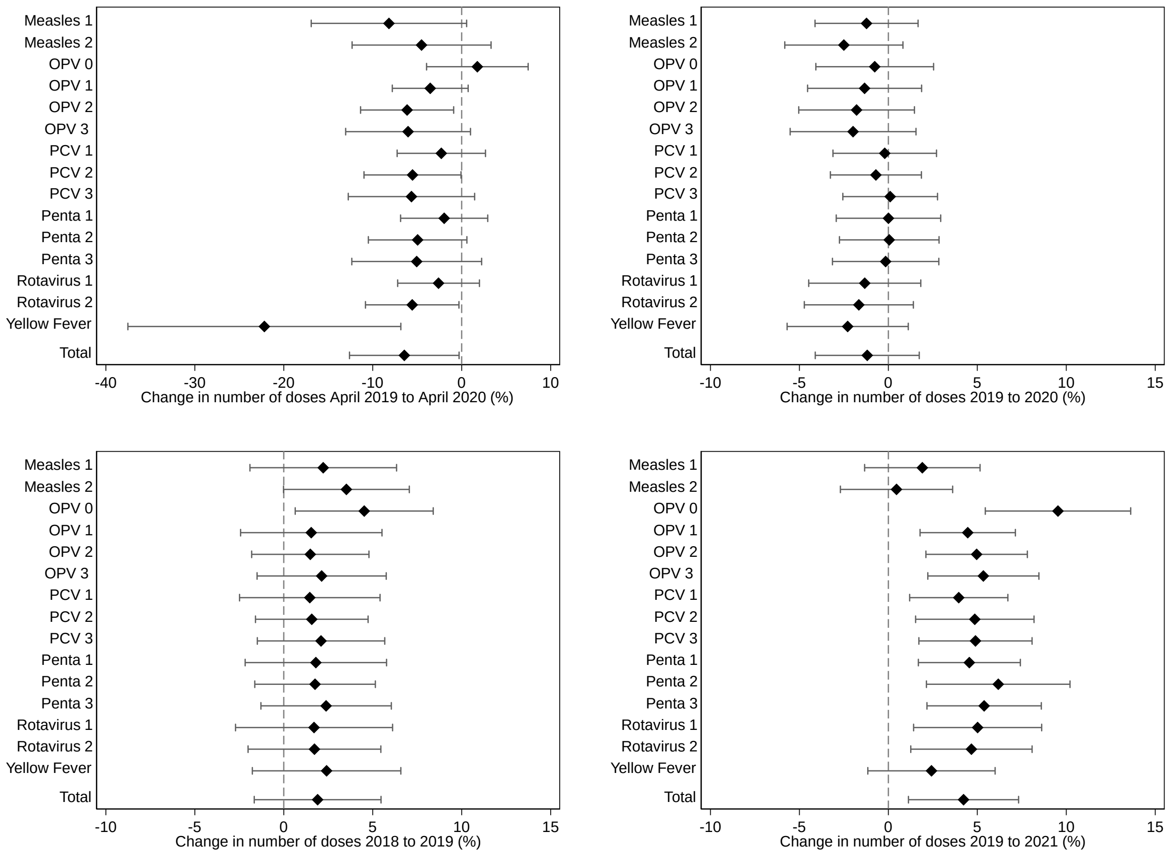


Figure 3: Development of routine child vaccinations by year and type
Note: Point estimates (dot) and the 95%-CI (line) are shown. The upper left figure shows the decrease from April 2019 to April 2020, the upper right figure the yearly doses decrease from 2019 to 2020, the lower left figure the yearly doses from 2018 to 2019, and the lower right figure from 2019 to 2020. All results are population growth adjusted the 95% confidence interval is shown.

	Number of doses (1)		Number of doses (2)	
Month*Year (ref. 2019)				
Feburary # 2018	-2.324	[-131.0,126.3]	-31.86	[-171.2,107.5]
March # 2018	-53.15	[-204.0,97.74]	-89.82	[-258.5,78.83]
April # 2018	0.730	[-152.0,153.4]	-23.56	[-199.8,152.7]
May # 2018	67.62	[-76.50,211.7]	57.07	[-105.8,219.9]
June # 2018	160.5	[-59.85,380.9]	158.4	[-87.67,404.5]
July # 2018	-1.883	[-268.4,264.6]	-13.74	[-275.2,247.7]
August # 2018	25.56	[-228.4,279.5]	41.72	[-198.0,281.4]
September # 2018	178.1	[-99.15,455.4]	168.1	[-141.6,477.9]
October # 2018	-173.6	[-442.2,95.10]	-173.5	[-440.0,93.09]
November # 2018	115.0	[-212.2,442.2]	131.7	[-185.8,449.1]
December # 2018	324.0**	[18.38,629.7]	328.8*	[-28.33,685.9]
Feburary # 2020	-207.2**	[-411.1,-3.388]	-217.0**	[-427.6,-6.479]
March # 2020	-343.1*	[-722.5,36.18]	-364.7*	[-778.3,48.85]
April # 2020	-494.7**	[-864.7,-124.7]	-493.0***	[-831.3,-154.6]
May # 2020	-102.0	[-342.8,138.8]	-66.32	[-337.6,204.9]
June # 2020	297.4***	[99.99,494.8]	379.1**	[53.33,704.9]
July # 2020	90.87	[-131.7,313.4]	238.2	[-106.3,582.8]
August # 2020	53.32	[-310.5,417.1]	118.1	[-253.3,489.6]
September # 2020	-103.9	[-364.5,156.8]	-119.8	[-404.0,164.5]
October # 2020	-268.9	[-719.8,182.0]	-265.3	[-747.0,216.4]
November # 2020	-32.56	[-272.6,207.5]	-11.17	[-290.2,267.9]
December # 2020	201.2**	[5.755,396.6]	222.1*	[-5.866,450.1]
Feburary # 2021	114.8	[-57.13,286.8]	138.3	[-35.40,311.9]
March # 2021	292.1**	[74.33,509.8]	212.5**	[36.52,388.4]
April # 20221	402.4***	[159.8,645.0]	303.0**	[48.56,557.5]
May # 20221	320.6***	[108.6,532.6]	222.6**	[16.68,428.6]
June # 20221	705.9***	[395.1,1016.6]	620.6***	[392.3,849.0]
July # 20221	377.9***	[116.8,639.1]	314.4***	[115.5,513.3]
August # 2021	484.9***	[189.7,780.1]	501.0***	[187.2,814.9]
September # 2021	715.6***	[281.9,1149.3]	667.0***	[287.8,1046.3]
October # 2021	107.4	[-74.00,288.8]	13.18	[-243.7,270.1]
November # 2021	313.4**	[26.01,600.8]	210.9	[-50.94,472.7]
December # 2021	177.3	[-305.2,659.7]	162.4	[-382.9,707.8]
Constant	5400.1***	[4473.2,6327.0]	151.3	[-641.4,944.0]
Month fixed effects	X		X	
Year fixed effects	X		X	
Vaccine level			X	
District control variables			X	
Regional COVID cases			X	
Observations	12480		11328	
R-squared	0.004		0.922	

Table 1: OLS regression of number of total monthly doses 2018-2021

Note: Only the month and year interaction term of equation (2) are shown. Robust regional clustered standard errors were used; 95% confidence interval in parenthesis; * p<0.05, ** p<0.01, *** p<0.001. All results are population growth adjusted. Vaccine level refers to the average number of doses administered in 2018 and 2019 at the district level. District control variables include: number of births, population density and poverty rate at districts level. Regional COVID cases refer to the monthly number of COVID cases at regional level.

	Number of doses January – December (1)		Number of doses January (2)		Number of doses February (3)		Number of doses March (4)		Number of doses April (5)		Number of doses May-December (6)	
Lockdown and COVID-19 impact status *Year (ref. lockdown-affectd districts with COVID-19 cases # 2019)												
Neighbor districts with COVID # 2018	-31.58	[-342.6,279.5]	284.8	[-655.5,1225.0]	700.9	[-241.6,1643.3]	239.3	[-626.1,1104.6]	368.1	[-424.4,1160.7]	-251.7	[-656.8,153.4]
Neighbor districts COVID # 2018	155.5	[-154.7,465.7]	344.5	[-573.5,1262.6]	887.3*	[-77.35,1852.0]	398.6	[-462.6,1259.7]	441.3	[-364.3,1247.0]	-32.61	[-437.1,371.9]
Other districts with COVID # 2018	121.5	[-189.6,432.5]	418.2	[-502.2,1338.6]	981.3**	[32.17,1930.5]	460.4	[-433.8,1354.6]	601.0	[-192.0,1394.0]	-130.2	[-535.4,275.0]
Other districts without COVID # 2018	245.1	[-57.62,547.8]	601.6	[-304.6,1507.8]	1109.1**	[173.7,2044.6]	652.3	[-178.9,1483.5]	891.6**	[113.6,1669.6]	-44.02	[-438.6,350.6]
Neighbor districts with COVID # 2020	617.3***	[231.7,1003.0]	645.9	[-295.5,1587.3]	1201.1**	[64.11,2338.1]	1230.6**	[28.01,2433.1]	1543.7***	[541.3,2546.1]	344.3	[-160.2,848.8]
Neighbor districts without COVID # 2020	695.7***	[328.3,1063.0]	557.5	[-353.6,1468.6]	1263.5**	[130.8,2396.1]	1336.4**	[132.8,2540.0]	1516.0***	[506.0,2525.9]	452.9*	[-20.44,926.2]
Other districts with COVID # 2020	572.9***	[200.2,945.5]	724.3	[-196.8,1645.5]	1340.7**	[194.7,2486.6]	1224.9*	[-12.75,2462.6]	1550.1***	[524.9,2575.2]	250.2	[-230.0,730.5]
Other districts without COVID # 2020	731.4***	[372.2,1090.5]	749.2	[-149.1,1647.4]	1317.1**	[200.3,2433.8]	1387.7**	[201.1,2574.3]	1970.4***	[997.3,2943.5]	415.3*	[-46.99,877.5]
Neighbor districts with COVID # 2021	135.0	[-232.6,502.7]	730.9	[-460.5,1922.4]	783.9	[-388.6,1956.3]	-163.2	[-1392.5,1066.1]	43.57	[-972.2,1059.3]	21.35	[-451.9,494.6]
Neighbor districts without COVID # 2021	211.2	[-144.4,566.8]	691.3	[-446.1,1828.8]	699.6	[-448.9,1848.2]	-62.32	[-1255.4,1130.8]	286.4	[-708.9,1281.8]	105.9	[-351.2,563.0]
Other districts with COVID # 2021	137.2	[-215.3,489.8]	591.4	[-557.6,1740.4]	918.4	[-235.9,2072.8]	-137.7	[-1367.2,1091.8]	356.0	[-668.3,1380.3]	-13.10	[-461.9,435.7]
Other districts without COVID # 2021	52.34	[-285.5,390.2]	592.7	[-521.9,1707.3]	780.0	[-350.1,1910.1]	-89.16	[-1260.0,1081.6]	322.6	[-656.3,1301.6]	-129.7	[-558.9,299.6]
Constant	537.4***	[204.5,870.4]	697.9	[-420.5,1816.4]	950.4	[-249.5,2150.4]	843.4	[-275.4,1962.2]	887.4*	[-84.90,1859.8]	506.6**	[106.6,906.7]
Month fixed effects	X										X	
Year fixed effects	X		X		X		X		X		X	
Lockdown and COVID-19 impact status fixed effect	X		X		X		X		X		X	
Vaccine level	X		X		X		X		X		X	
District control variables	X		X		X		X		X		X	
Observations	11328		944		944		944		944		7552	
R-squared	0.922		0.935		0.932		0.923		0.941		0.919	

Table 2: OLS regression of absolute number of total monthly doses 2018-2021 by lockdown and COVID impact status.

Note: Only the impact status and year interaction term of equation (3) are shown. Robust standard errors were used; 95% confidence interval in parenthesis; * p<0.05, ** p<0.01, *** p<0.001. All results are population growth adjusted. Vaccine level refers to the average number of doses administered in 2018 and 2019 at the district level. District control variables include: number of births, population density and poverty rate at districts level. Lockdown and COVID-19 impact status fixed effect refers to the five categories "Neighbor of lockdown-affected districts with COVID cases", "Neighbor of lockdown-affected districts without COVID cases", "Other districts with COVID cases", "Other districts without COVID cases" and "Lockdown-affected districts with COVID cases" (see S2 in the Appendix).

Appendix

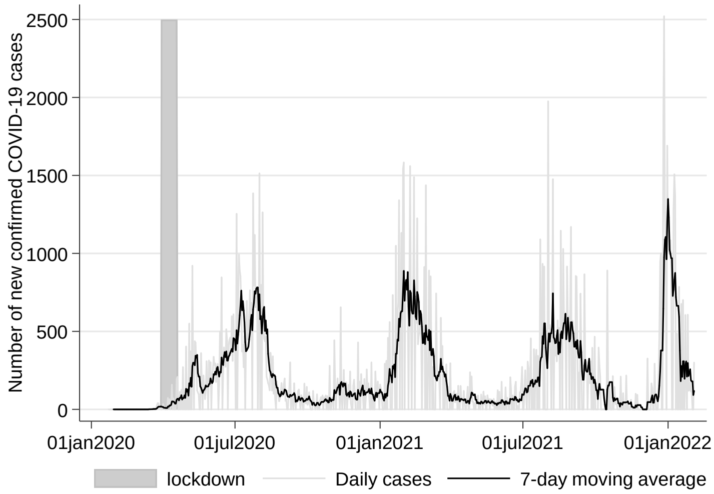


Figure A.1: Daily new confirmed COVID-19 cases in Ghana since January 1, 2020
Note: The seven-day moving average was calculated as the average of the daily number and the six lags. The gray shaded area indicates the period of the geographically concentrated public lockdown in Ghana (March 29 to April 19, 2020).
Source:Johns Hopkins (2021) —last updated February 8, 2022.

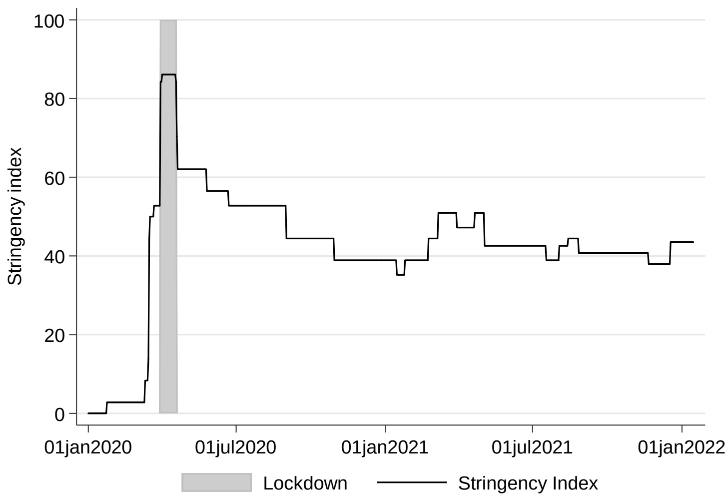


Figure A.2: Stringency index from Ghana since January 1, 2020
Note: The Government Response Stringency Index is a composite measure based on nine response indicators, including school closures, workplace closures, and travel bans, rescaled to a value from 0 to 100 (100 = strictest response). This index should not be interpreted as "scoring" the appropriateness or effectiveness of a country's response; it simply records the number and the strictness of government policies. The gray shaded area indicates the period of the geographically concentrated public lockdown in Ghana (March 29 to April 19, 2020).
Source: Hale et al. (2022)—last updated February 8, 2022.

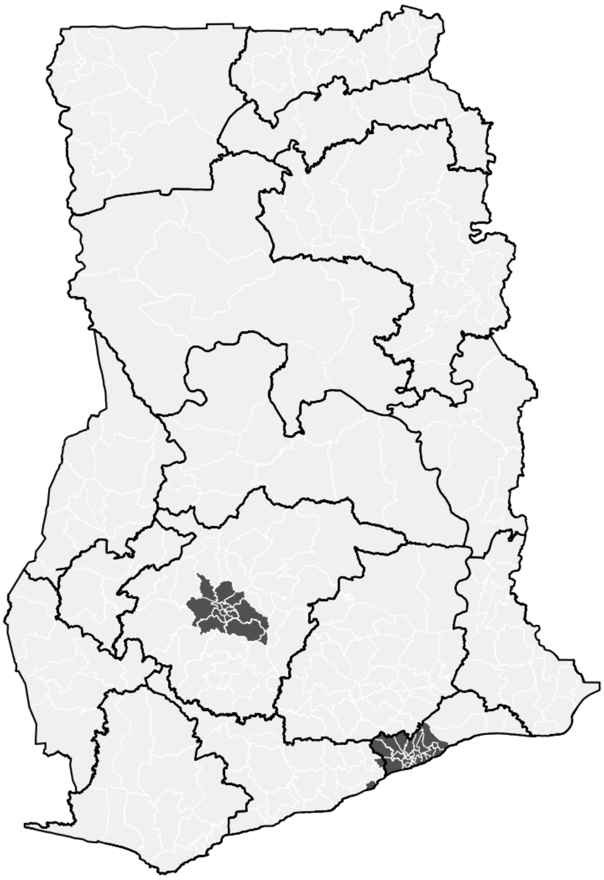


Figure A.3: Lockdown impact status of districts in Ghana
Note: Out of the 260 districts in Ghana, 40 districts were under lockdown in April 2020 (dark gray areas) and 220 districts were not affected by the lockdown (light gray areas).

	Number of doses, Non lockdown-affected districts (1)		Number of doses, Lockdown-affected districts (2)	
Month*Year (ref. 2019)				
Feburary # 2018	45.91	[-52.47,144.3]	-457.9	[-1749.6,833.9]
March # 2018	-82.57	[-254.5,89.33]	-113.3	[-1379.5,1153.0]
April # 2018	8.801	[-169.8,187.4]	-201.1	[-1414.2,1012.0]
May # 2018	-35.13	[-173.5,103.3]	575.7	[-814.1,1965.5]
June # 2018	62.75	[-110.5,236.0]	700.5	[-595.6,1996.6]
July # 2018	-5.695	[-220.4,209.0]	-54.45	[-1307.9,1199.0]
August # 2018	-3.314	[-183.5,176.9]	285.4	[-1137.3,1708.0]
September # 2018	-5.066	[-264.7,254.5]	1135.7	[-329.2,2600.6]
October # 2018	-180.6	[-428.3,67.04]	-123.9	[-1485.1,1237.3]
November # 2018	23.56	[-215.2,262.4]	744.4	[-965.0,2453.7]
December # 2018	115.3	[-187.0,417.7]	1465.9**	[33.14,2898.6]
Feburary # 2020	-139.3***	[-234.8,-43.74]	-642.1	[-2154.4,870.2]
March # 2020	-285.2***	[-485.9,-84.56]	-825.2	[-2434.4,784.1]
April # 2020	-360.2***	[-515.1,-205.3]	-1361.5*	[-2773.4,50.49]
May # 2020	-168.2**	[-331.4,-5.075]	102.5	[-1442.5,1647.4]
June # 2020	135.7	[-90.48,362.0]	1129.9	[-442.7,2702.4]
July # 2020	5.152	[-223.6,234.0]	365.3	[-1198.2,1928.8]
August # 2020	-20.16	[-430.7,390.4]	345.9	[-1251.9,1943.7]
September # 2020	-231.7	[-529.8,66.39]	366.7	[-1302.6,2036.1]
October # 2020	-227.7	[-537.7,82.37]	-560.9	[-2298.3,1176.6]
November # 2020	-134.3	[-394.2,125.6]	464.5	[-1365.6,2294.6]
December # 2020	78.26	[-141.1,297.7]	792.2	[-1020.0,2604.3]
Feburary # 2021	115.3	[-77.78,308.5]	5.047	[-1563.5,1573.6]
March # 2021	146.5	[-57.24,350.2]	950.8	[-665.1,2566.7]
April # 20221	335.9**	[63.74,608.0]	748.6	[-699.2,2196.3]
May # 20221	203.6*	[-38.94,446.1]	981.4	[-676.6,2639.5]
June # 20221	505.6***	[198.1,813.1]	1868.7**	[269.6,3467.8]
July # 20221	239.5*	[-0.524,479.6]	1011.7	[-519.2,2542.5]
August # 2021	338.3**	[19.32,657.3]	1207.6	[-393.3,2808.6]
September # 2021	533.8***	[193.2,874.4]	1706.4**	[74.43,3338.4]
October # 2021	136.9	[-79.94,353.8]	-81.78	[-1768.1,1604.5]
November # 2021	229.1*	[-49.45,507.7]	846.1	[-896.5,2588.8]
December # 2021	22.44	[-315.8,360.6]	915.2	[-665.1,2495.4]
Constant	75.48	[-79.29,230.3]	283.4	[-293.8,860.5]
Month fixed effects	X		X	
Year fixed effects	X		X	
Vaccine level				
District control variables	X		X	
Regional COVID cases	X		X	
Observations	9600		1728	
R-squared	0.917		0.908	

Table A.1: OLS regression of number of total monthly doses 2018-2021 by lockdown status

Note: Only the month and year interaction term of equation (2) are shown. Robust regional clustered standard errors were used for column (1) and robust standard errors were used for column (2); 95% confidence interval in parenthesis; * $p<0.05$, ** $p<0.01$, *** $p<0.001$. All results are population growth adjusted. Vaccine level refers to the average number of doses administered in 2018 and 2019 at the district level. District control variables include: number of births, population density and poverty rate at the district level. Regional COVID-19 cases refer to the monthly number of COVID-19 cases at regional level.

S1: Routine Child Immunization Data

As listed in Table S.1, all children should be vaccinated per Ghana's recommended immunization schedule. Children with any missed doses should receive "catch-up" vaccines within the first five years of the child's life. Exceptions are the four time-critical vaccinations: OPV/Polio 0, BCG and Rotavirus 1 & 2. OPV/Polio 0, and BCG should be given at birth or at least within the first two weeks,[7] whereas the Rotavirus vaccine at weeks 20 and 24. Most vaccinations require more than one dose for the development of adequate antibody response. A minimum interval of two weeks between each dose is recommended. A longer interval does not necessarily reduce the final antibody response (if the maximum age is adhered to), but it extends the time when the child is at risk of developing the disease. The numbers for the IPV and MenA vaccine will be excluded from our analysis to avoid bias due to the recent introduction of IPV in June 2018 and the anyway decreasing trend of MenA. For BCG, we only received the data until the year 2020 and therefore also excluded it from the analysis. Nevertheless, the results up to 2020 follow the same trend as other time-critical vaccinations, such as Polio 0 (results available from authors upon request).

All routine child immunizations are given out for free at all points of care in Ghana, even to those not covered by the National Health Insurance Scheme (NHIS). The distribution of the vaccines is planned based on the Expanded Program on Immunization (EPI) Plan of Ghana and given out (i) in the hospital at all levels of health care, (ii) by outreach of Community-based Health Planning and Services (CHPS), and (iii) by national immunization campaigns in cooperation with the the Ministry of Health and health partners. The latter includes only the following vaccine types: Measles/Rubella, Yellow Fever, Polio and MenA (WHO, 2018b; 2018c; 2020e; Gavi, 2020b).

In line with the general trend of routine child vaccination coverage in Ghana, the data shows that almost all vaccinations in 2020 were on a similar level of around 1,100,000 total doses administered within a year in the entire country, corresponding to a coverage rate of around 97% of the target population (WHO, 2020e). Although Polio 0 has a lower absolute level (around 900,000 doses yearly), this still corresponds to a high coverage rate of up to 97% since the target population is children younger than two weeks and therefore we expect a smaller number than vaccines for children below five years old. There is a lower absolute level of total doses for Measles Rubella 1 & 2, Rotavirus 2, and Yellow Fever, which is again in line with the official WHO-UNCEF coverage rates, corresponding to a coverage rate of around 80% (WHO, 2020e). Therefore, we do not assume any bias due to data quality.

For our analysis it is important to mention that a Polio campaign scheduled for April and May 2020 in eight regions in Ghana as well as a national Yellow Fever campaign scheduled in April 2020 both had to be postponed to September and October 2020 and to November 2020 (Gavi, 2020b), respectively, due to the COVID-19 pandemic. The re-launch was only possible since all vaccinators, volunteers, and supervisors were trained on COVID-19 prevention protocols and had been provided with personal protective equipment (PPEs) to ensure optimal infection prevention (WHO, 2020e).

[7] BCG preferable not beyond two weeks, however, at maximum within the first year.

Table S.1: Overview of vaccine-preventable diseases targeted by Expanded Programme on Imunization (EPI) in Ghana

Disease	Associated Vaccine used in Ghana	Min. Age	Max. Age	Indicator
Measles	Measles-Rubella vaccine	9 months	<5years	Measles Rubella 1
Rubella & Congenital Rubella Syndrome				Measles Rubella 2
Poliomyelitis	Oral polio vaccine (OPV)	Birth	<2weeks	OPV/Polio 0
		6 weeks	<5 years	OPV/Polio 1
				OPV/Polio 2
				OPV/Polio 3
Pneumonia, mengitis, other IPD	Pneumococcal vaccine	6 weeks	<5 years	PCV 1
				PCV 2
				PCV 3
Diphtheria	Component of Pentavalent (DPT-Hib-HepB) and Td vaccines	6 weeks	<5 years	Penta 1
Tetanus	Component of Pentavalent (DPT-Hib-HepB) and Td vaccines			Penta 2
Pertussis or Whooping cough	Component of Pentavalent (DPT-Hib-HepB) vaccine			Penta 3
Viral hepatitis	Component of Pentavalent (DPT-Hib-HepB) and HepB vaccines			
Pneumonia, mengitis, Septicaemia etc.	Component of Pentavalent (DPT-Hib-HepB) vaccine			
Rotavirus diarrhea	Rotavirus vaccine	6 weeks	1st dose: 20 weeks	Rotavirus 1
			2nd dose: 24 weeks	Rotavirus 2
Yellow fever	Yellow fever vaccine	9 months	<5 years	Yellow Fever
Tuberculosis (TB)	*Bacillus Calmette-Guérin (BCG) vaccine*	*Birth*	*<1 year*	*BCG*
Poliomyelitis	*Inactivated polio vaccine (IPV)*	*14 weeks*	*<5 years*	*IPV*
Meningococcal meningitis	*Conjugate Meningococcal A (MenAfriVac)Vaccine*	*18 months*	*<5 years*	*MenA*

Note: Based on the EPI Ghana, for each vaccination the minimum and maximum age for the dose are listed as well as the corresponding indicator in our data.
Source: Ghana Health Services, 2021.

S2: Lockdown and COVID-19 impact status

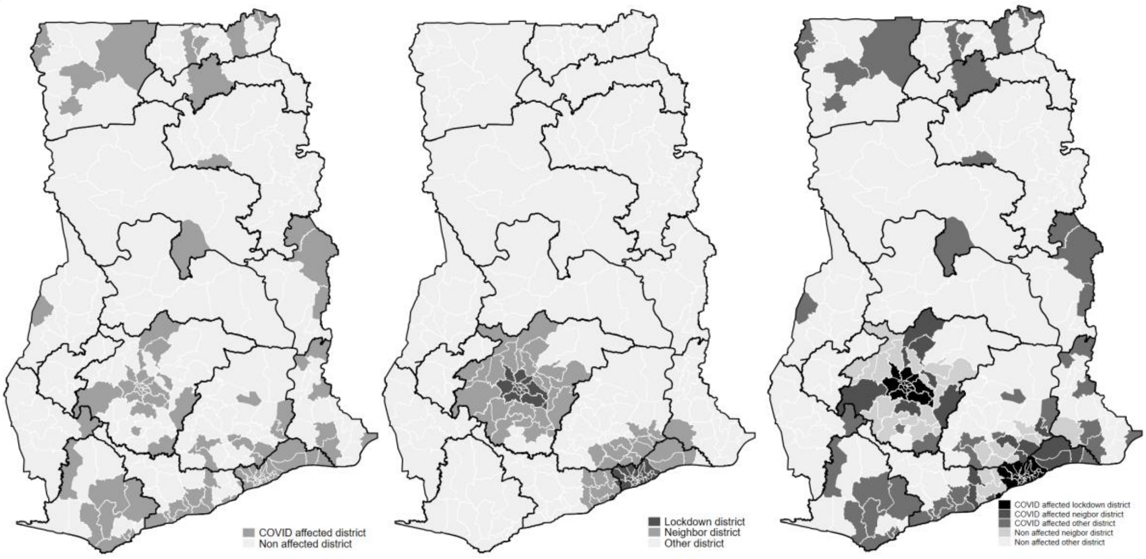
As stated in Section 2.1, the Ghanaian government introduced a geographically concentrated public lockdown in 40 of the most affected districts in the Greater Accra Metropolitan Area and Greater Kumasi Metropolitan Area from March 30 to April 19, 2020 (Figure A.3; Republic of Ghana, 2020a).

It is important to note that at that time, not only the lockdown-affected districts had COVID-19 cases, but also 63 additional districts all over the country (Figure S.1, left panel). We do not have access to data on the intensity of COVID-19 cases per district, but we can use the binary information indicating whether a district was affected by COVID-19 in April 2020 that was published in Ghana's outbreak response management updates (GHS, 2022).

Using a simple OLS regression to analyze which COVID-19 affected districts were put under lockdown reveals that besides the intensity, population density and wealth were also highly correlated. Because the 220 non lockdown-affected districts significanty differ in terms of population, socioeconomic factors, and urbanization, we also create a three-level categorical variable (Figure S.1, middle panel) to indicate whether the district was affected by the geographically concentrated public lockdown in April 2020, if the district was a first- or second-order neighbor of a lockdown-affected district (with the assumption that these are very similar to lockdown-affected districts in terms of population, socioeconomic factors, and urbanization, as well as fear of COVID-19 exposure, but different in terms of restrictions), and if the district was not affected by the geographically concentrated public lockdown in April 2020 and is not further away from a lockdown-affected district. Therefore, we categorize 40 districts as lockdown-affected districts, 45 districts as neighbor districts, and 175 districts as other districts.

Putting together the information on which districts were affected by COVID-19 in April 2020, as well as on which districts were closer to the lockdown hotspot, we created a five-level categorical variable (Figure S.1, right panel) to indicate if a given district was affected by the geographically concentrated public lockdown in April 2020 (40 districts), if a district was a neighbor of a lockdown-affected district and also experienced COVID-19 cases in April 2020 (17 districts), if the district was an "other" district and also experienced COVID-19 cases in April 2020 (46 districts), if the district was a neighbor of a lockdown-affected district but did not experience COVID-19 cases in April 2020 (28 districts), or if the district was an "other" district but did not experience COVID-19 cases in April 2020 (129 districts).

Figure S.1: Lockdown and COVID-19 affected districts in Ghana



Note: The left figure shows which districts had COVID-19 in April 2020. The middle figure shows in addition to Figure A.3 the neighbor districts (highlighted in light gray). The right figure shows the five-level lockdown and COVID-19 impact status variable.

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