A model of COVID-19 pandemic evolution in African countries taking into account the impact of vaccination

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Abstract

We studied the COVID-19 pandemic evolution in selected African countries. For each country considered, we modeled simultaneously the data of the active, recovered and death cases.

Keywords: COVID-19, $SIDARTHEV$, Basic Reproduction Number, SARS-CoV-2, Vaccination

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1. Introduction

Coronavirus disease 2019 (COVID-19) that is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) continues to spread across the globe since 2019 [1]. COVID-19 continues to spread in spite of the implementation of different control measures such as social distancing, wearing of face masks, sanitation, lock-down, vaccination and many more.

To Be Continued

The rest of the paper is organised as follows. In Section 2, we present the formulation of $SIDARTHEV$ model taking into account infectious vaccinated individuals. In Subsection 2.1, we present the analysis of COVID-19 data taking into account the transmission dynamics of COVID-19 since the vaccination program started in each country of the following countries: South Africa, Mozambique, Cameroon, Nigeria, Togo, and Zambia considered in this study. In Section 4, we present the discussion of the analysis of COVID-19 data results followed by discussion and conclusion, respectively.

2. Formulation of $SIDARTHEV$ model taking into account infectious vaccinated individuals

The model presented in this section is the extension of the SIDARTHE model that we considered in the previous study [9]. In this study, we focus on the results during the vaccination process using the $SIDARTHEV$ model, but relying on the SIDARTHE model for those sections where vaccination data is lacking. Contrary to the $SIDARTHE$ model which is based in the assumption that all vaccinated are immunized, $SIDARTHEV$ model assumes that vaccinated, in the V compartment, can still get infected and become infectious just like for non-vaccinated susceptible, in the S compartment. It is observed that a few portion of the vaccinated but infected, in the I_2 compartment, are threatened by the disease. The new model captures this dynamics by connecting the I_2 compartment to the T compartment. This results into the diagram below

2

Susceptible–Infected-Diagnosed-Ailing-Recognized-Threatened-Healed-Extinct-Vaccinated-Infected (SIDARTHE-VI)

SIDARTHE-VI Parameters:
- **α, γ: Transmission rate due to contact with UNDETECTED asymptomatic, symptomatic infected, respectively.**
- **β, δ : Transmission rate due to contacts with DETECTED asymptomatic, symptomatic infected, respectively.**
- **ε: Detection rate for ASYMPTOMATIC**
- **θ: Detection rate for SYMPTOMATIC**
- **ζ: Worsening rate, UNDETECTED asymptomatic infected becomes symptomatic**
- **η: Worsening rate , DETECTED asymptomatic infected becomes Symptomatic**
- **μ: Worsening rate, UNDETECTED symptomatic infected develop life–threatening symptoms.**
- **ν: Worsening rate, DETECTED symptomatic infected develop life - threatening symptoms.**
- **κ, λ: Recovery rate for undetected asymptomatic, symptomatic infected, respectively.**
- **ξ, ρ: Recovery rate for detected asymptomatic, symptomatic infected, respectively.**
- **φ: vaccination rate**
- **α′: Reinfection rate of vaccinated**
- **τ₁, τ₂: Mortality rate for recognized infected and for infected with life-threatening symptoms**
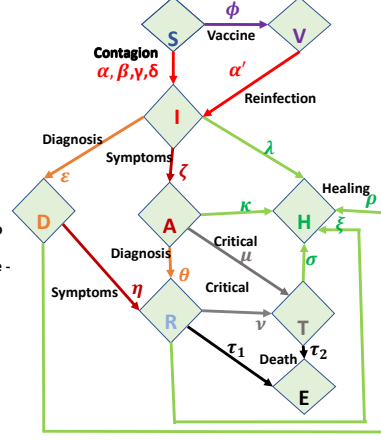
Figure 1: Flow-chart representing the $SIDARTHEV$ model taking account infectious vaccinated individuals.

The addition of these new connections have changed the partial differential equations of the $SIDARTHEV$ model to the following

$$
\begin{cases}
\dot{S} &= -\left(\alpha I + \beta D + \gamma A + \delta R\right)S - \phi S \\
\dot{V} &= -\alpha' IV + \phi S \\
\dot{I} &= \left(\alpha I + \beta D + \gamma A + \delta R\right)S + \alpha' IV - \left(\epsilon + \lambda + \zeta\right)I \\
\dot{D} &= \epsilon I - \left(\eta + \rho\right)D \\
\dot{A} &= \zeta I - \left(\theta + \mu + \kappa\right)A \\
\dot{R} &= \eta D + \theta A - \left(\tau_1 + \nu\right)R \\
\dot{T} &= \mu A + \nu R - \left(\tau_2 + \sigma\right)T \\
\dot{H} &= \lambda I + \kappa A + \sigma T + \xi R + \rho D \\
\dot{E} &= \tau_1 R + \tau_2 T
\end{cases}
\tag{1}
$$

2.1. The basic reproduction number

The basic reproduction number plays an vital role in mathematical epidemiology; it is the average number of secondary cases produced by an infected indi-

vidual in a population where everyone is susceptible [8]. The basic reproduction number derived from the $SIDARTHEV$ model 1 is given by

$$R_0 \quad = \quad \frac{\alpha r_2 r_3 r_4 + \beta \epsilon r_3 r_4 + \delta \epsilon \eta r_3 + \delta r_2 \tau \zeta + \gamma r_2 r_4 \zeta}{r_1 r_2 r_3 r_4}, \tag{2}$$

where $r_1 = \epsilon + \zeta + \lambda$, $r_2 = \eta + \rho$, $r_3 = \theta + \mu + \kappa$, $r_4 = \nu + \xi$. Derivation of the basic reproduction number, R_0 is found in [2]. As shown in Equation 2, R_0 depends on the model parameters that affect pandemic evolution. The aim of this analysis was to estimate R_0 with model parameters that describe the real data. Therefore, it is important to understand the model parameters and to make sure they are extracted correctly.

3. Analysis of COVID-19 data

3.1. Analysis of COVID-19 data of South Africa

In South Africa, Covid-19 vaccination is an ongoing immunisation campaign against SARS-CoV-2 which aims to vaccinate 40 million South Africans [3]. There are four types of Covid-19 vaccines that have been approved for use in South Africa by the South African Health Products Regulatory Authority (SAHPRA), namely, Johnson Johnson, Pfizer, Sinovac and AstraZeneca [3]. For South Africa Covid-19 case study, Johnson & Johnson's Janssen vaccine and Pfizer vaccine are considered. (i)Johnson & Johnson's Janssen vaccine: It is a viral vector vaccine based on a human adenovirus that has been modified to contain the gene for making the spike protein of the SARS-CoV-2 virus that causes COVID-19 [4]. The body's immune system responds to this spike protein to produce antibodies [5]. This vaccine does not need to be stored frozen and requires only one dose [6], [7]. Only people of the age 18 and older can take this vaccine. A person is considered fully vaccinated two weeks after one shot [1]; (ii) Pfizer vaccine: Only people of the age 16 and older can take Pfizer vaccine. It is administered in two shots. A person is considered fully vaccinated two weeks after the second shot [1].

In our previous study we covered the South African COVID-19 data up to adjusted alert level 3 that was effect from 29 December 2020 to 28 February 2021 [9]. Based on the changes of COVID-19 new cases in South Africa, the government introduced adjusted alert levels as follows:(i) from the 1st of October 2021 to the 4th of April 2022 South Africa was at adjusted alert level 1, (ii) from the 13th to the 30 September 2021 South Africa was at adjusted alert level 2, (iii) from the 26th of July to the 26th of September 2021 South Africa was at adjusted alert level 3, and (iv)from the 28th of June 2021 until 25th of July 2021, South Africa was at adjusted alert level 4 [3]. As of 3rd of May 2022, South Africa has confirmed $3,661,635$ recovered individuals, $100,377$ death cases and $34,941,461$ vaccinated individuals, $3,802,198$ positive cases [3]. The National State of Disaster in South Africa has been lifted since 5 April 2022 [10].
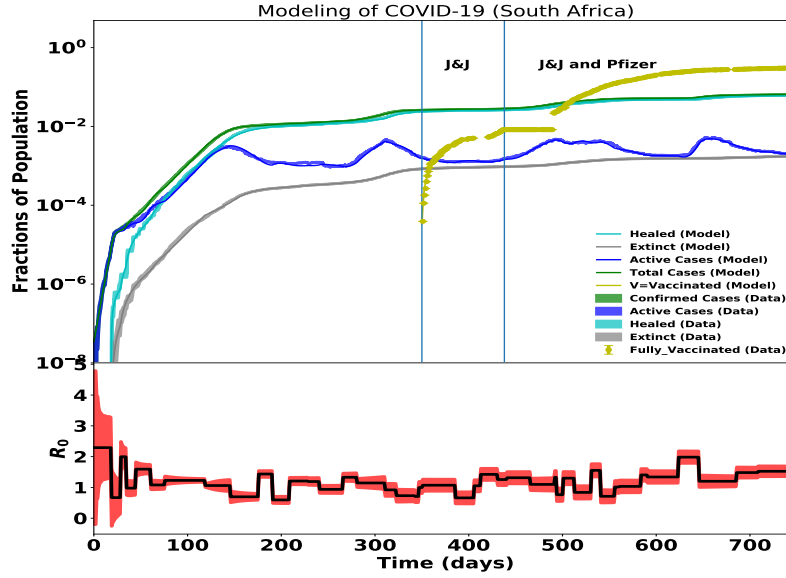
Figure 2: Graphs showing COVID-19 data and $SIDARTHEV$ model of South Africa taking into account the Active, Healed, Extinct, Vaccinated and Total cases over time in days since the 28th of February 2021 up to the 20th of March of 2022 over time in days are shown in the top plot. The time dependent basic reproduction number is represented in the bottom plot.

3.2. Analysis of COVID-19 data of Mozambique

In Mozambique the vaccination starts on March 8, 2021, at the end of the first year of COVID-19 occurrence and in the period when we were coming out of the second wave that had its peak at the end of January 2021 and by March when vaccination was implemented there was already a reduction of active cases due to non-pharmaceutical measures such as the implementation of Decree no 7/2021 of March 05 (see on [11]) on March 07 2021, which was one day before the start of the vaccination campaign. This first vaccination campaign targeted health professionals

The continuity of vaccination data after the first gap (between days 350 and 500) of vaccination data is seen at the peak of the third wave where we can
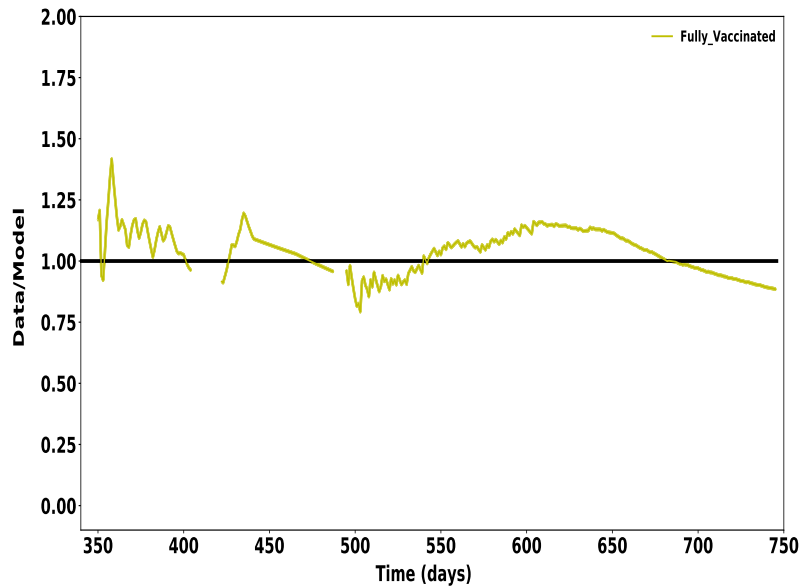
6

Figure 3: The plot showing the goodness-of-fit of the COVID-19 data modelling of South Africa for fully-vaccinated individuals over time in days since the 28th of February 2021 up to the 20th of March of 2022.

see a reduction in active cases and an increase in recovered cases without much variation in the dead data.

The fourth wave (omicron wave) was the most infectious wave, having an initial growth close to 90 percent but which did not take long period of time compared to other waves, and return to stability compared to the other waves, where the concept of booster dose was introduced which has the function of re-immunising people and should be administered 6 months after the last immunization [13]. Figure 5 represents the following data sets: total data infected (green), active (blue), recovered (light blue), dead (gray), fully vaccinated (yellow) which are people who received two doses or one dose of Johnson Johnson- that already guarantees immunity, vaccinated with one dose that does not guarantee immunity yet (red), vaccinated with the booster dose (pink) and we also have the

7

fitted model curves in the first 5 data sets described here. The first vertical bar between days 300-400 (day 349) demarcates the day of vaccination initiation, where the sinopharm vaccine was administered; the second bar (day 500) demarcates the introduction of the Astrazeneca vaccine and the third bar near day 600 (day 583) describes the day of implementation of Johnson   Johnson single dose vaccination.
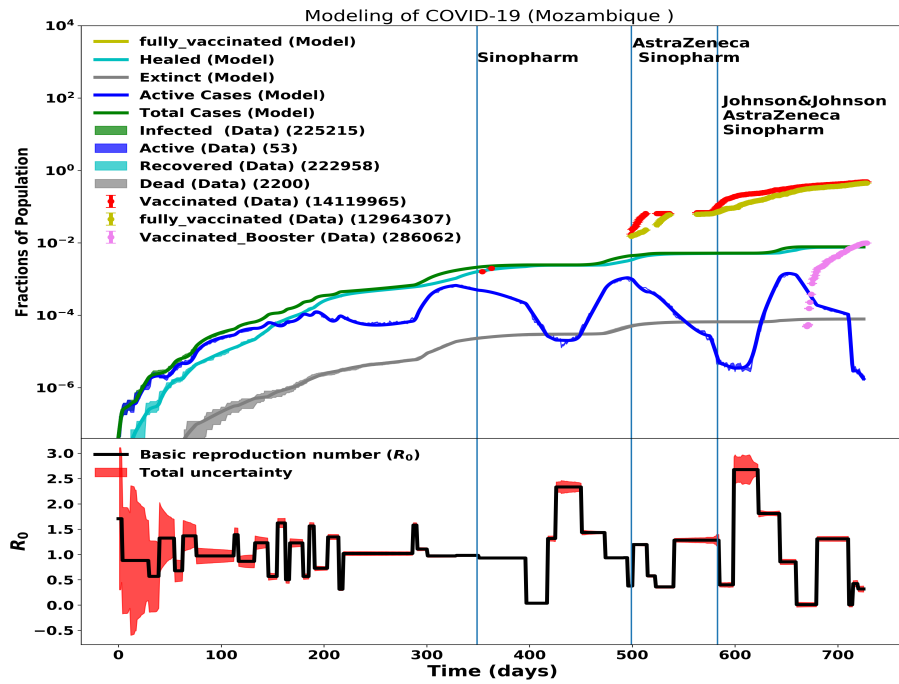

Figure 4: Graphs showing COVID-19 data and SIDARTHEV model of Mozambique taking into account the Active, Healed, Extinct, Vaccinated and Total cases over time in days since the 22nd of March 2020 up to the 22nd of March of 2022 over time in days are shown in the top plot. The time dependent basic reproduction number is represented in the bottom plot.

3.3. Analysis of COVID-19 data of Nigeria from the emergence of the disease

In Nigeria, they confirmed the first case in the Infectious Disease Centre, Yaba, Lagos State, Nigeria on the 27th of February, 2020. An airline from Milan, Italy arrived at the International Airport, Lagos on the 24th of February,
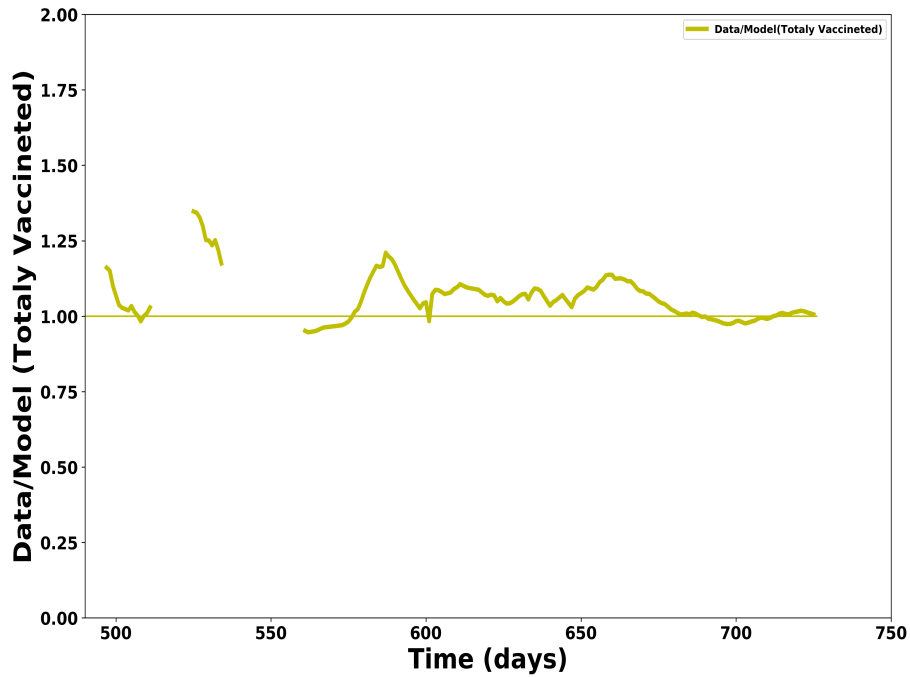
Figure 5: The plot showing the goodness-of-fit of the COVID-19 data modelling of Mozambique for fully-vaccinated individuals over time in days since the 22nd of March 2020 up to the 22nd of March of 2022.

2020 with an infected Italian citizen who went to his company's site in Ogun State the following day. The health authorities (Nigeria Centre for Disease Control) implemented containment measures by the contact tracing of 'Persons of Interest' which included all persons on the manifesto of the flight and those he had close contact with while in Lagos and Ogun State. After a period of two weeks, cases were detected in Lagos and Abuja and this marked the emergence of the spread in the country. The Federal Government restricted international commercial flights into the country, effective from 23rd March 2020.

The Federal Government ordered the closure of schools and all the non-essential services (businesses and industries) and ordered cessation of all movements in Lagos State, Ogun State and the Federal Capital Territory, Abuja, on 29th March 2020 for an initial period of 14 days and later extended it with

another 14 days on 12th April 2020 [17, 18]. Most State Governments restricted public gatherings and religious activities for over fifty (50) persons. The Federal Government lifted the travel ban on domestic flights on the 20th of April 2020. The Federal Government ordered a Nationwide overnight curfew from 8:00 pm to 6:00 am on the 2nd May 2020 and later eased the overnight curfew to be from 12:00 am to 4:00 am. The Federal Government later authorized the gradual easing of lockdown in the previously restricted states on the 4th of May 2020 and mandated the use of face masks in public. On the 6th of May 2020, the Federal Government extended the travel ban on both International and local flights to 7th June 2020. The Federal Government reopened the international flight for operations on 29th August 2020 [16]. On the 27th of January 2021, the President signed six COVID-19 Health Protection Regulations 2021, with restrictions on gatherings, operations of public places, mandatory compliance with treatment protocols, offences and penalties, enforcement and application and lastly the interpretation and citations of the regulations [20]. After the first confirmed case on 27th February 2020, the number of confirmed cases increased drastically and the total number of confirmed cases as of 28th February 2022 is 254,560 with a total number of 249,079 discharged cases and 2,339 active cases. The first death case was on the 23rd March, 2020 and have increased to a total number of 3,142 death cases as of 28th February, 2022. The health sector started covid-19 sample test on the 8th April, 2020 and on the 28th February, 2022, they have recorded total tests of 4,317,621. The first shipment of four million Oxford-AstraZeneca covid-19 vaccine arrived the country on 2nd March and vaccination began on 5th March, 2021 with a doctor at National Hospital Abuja and the President received his first dose on 6th March, 2020 [19]. As of 28th February, 2022, 17,914,844 persons have received their first dose and 8,197,832 have received their second dose.

From Figure 6, the Nigeria COVID-19 plot, we have the COVID-19 data at the top panel; we superimpose the modeling of the data and see good agreement in the infected, active, recovered, and dead cases. As a result, the fully vaccinations are also well modeled except the data of the total vaccinations. From the
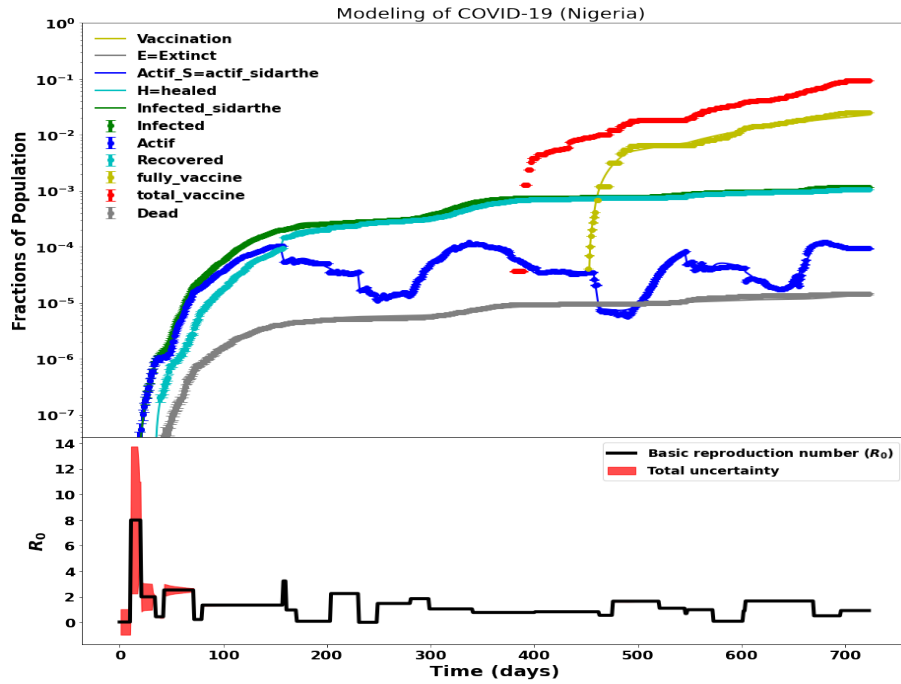
Figure 6: Graphs showing COVID-19 data and SIDARTHEV model of Nigeria taking into account the Active, Healed, Extinct, Vaccinated and Total cases over time in days since the..... of March 2019 up to the .... of March of 2022 over time in days are shown in the top plot. The time dependent basic reproduction number is represented in the bottom plot.

modeling, we derive R_0 for Nigeria as shown in the bottom panel of the plot. The initial R_0 is zero and increases significantly to eight after a week because of the negligence from the public on the measures. Around day 35, the R_0 dropped below one mainly because of the quick reaction from the government. Another increase in R_0 to a point above two was observed around day 40. Around day 65, it also dropped below one. The R_0 later increase around day 75 above one and later rose to a point above three around day 150 due to ineffectiveness of the measures in some parts of the country. Around day 165, the R_0 dropped to zero and increased above two around day 205. Another drop occurred around day 230 to point zero after some restrictions from the government. We see that around day 250, there was an increase in R_0 above one and was about two
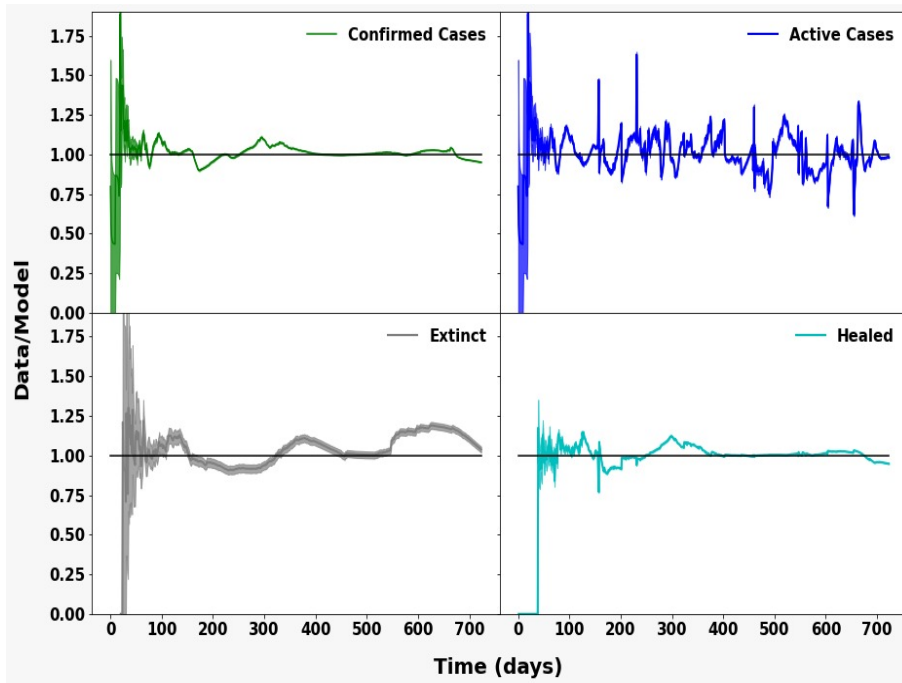
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Figure 7: ....

around day 280. It dropped in the subsequent months below one around day 458 and after day 470, R_0 was above one. However, we see another reduction in R_0 to point zero around day 570. After day 605, R_0 was about two and after several measures from the government, R_0 dropped below one around day 664. And we see that increase in R_0 was about one even after 700 days.

3.4. Analysis of COVID-19 data of Togo

3.5. Analysis of COVID-19 data of Ghana

3.6. Analysis of COVID-19 data of Cameroon

The case ratio for COVID-19 had been much lower than SARS of 2003 while the transmission had been greater, with an important total death toll [21, 23]. For Cameroon, models-based simulations indicate that the 95% confidence interval for the time-varying reproduction number Rt had been more stable at
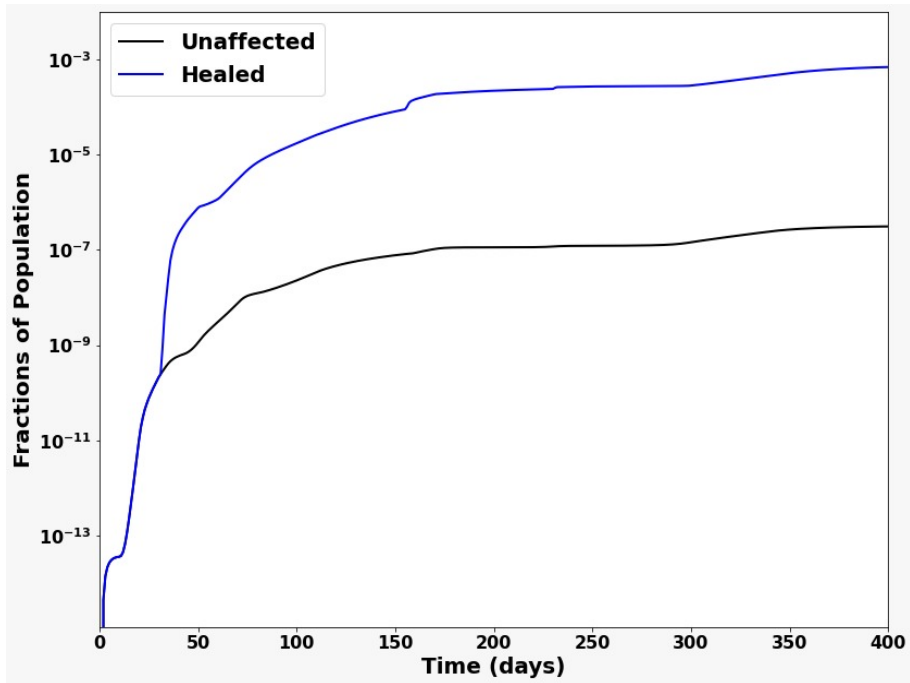
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Figure 8: ....

around 1.0 since August 2020 [23]. While the entire world is suffering from the pandemic, the Cameroon government was receiving some aid in particular. One of the richest men in the world Jack Ma donated some medical supplies to assist the effort of our government to fight the COVID-19 pandemic. His gift contained 20,000 test kits, 100,000 masks, 1,000 medical-use protectives suits, and face shields [25]. One of our best players Samuel Eto'o had given 50,000 facial protection masks to taxi drivers [26]. The first case of vaccination had started on 12 April 2021, with initially 200,000 doses of the Sinopharm BIBP vaccine donated by China [27].

Since the beginning of the year 2021, the number of death due to COVID-19 is sharply increasing and the Minister of public health is heard. In March, the minister confirmed the general relaxation of the population particularly his ministry with scientific committee meetings were given up. The minister pre-

13

pared the Cameroonian for the vaccination by saying:" We have the choice between the prevention by respecting the barrier measures and the prevention by vaccination. While the Government is getting ready to receive the first doses of vaccines obtained with the facility of OMS, 7 European countries declare the withdrawal of the AstraZeneca vaccine. The pandemic is tremendously increasing with more than 3000 affected in one week. After the death of Madam Adoum Gargoum who was the delegated minister to the external relationship in charge of Cooperation with the Islamic world, the country recorded his first high-level manager. In April, more than 22,000 contamination and 300 deaths in one month. The president of the republic ordered the opening of a judiciary investigation of authors, co-authors, and accomplices of financial embezzlement cases as part of the management of funds allocated to fight against COVID-19. The Government announced the arrival of 200,000 doses of vaccines from the Sinopharm firm. The priority of this was destinated to people more than 50 years old and nursing staff. The Government launched a communication campaign to deal with growing reluctance against vaccines while we reached the symbolic number of 1.000 death. The restrictions and measures against COVID-19 disturbed the fight against other diseases like the food aid which didn't arrive at the recipient's due to confinement measures. The Government member preached by example by being vaccinated with the first lot of about 400 thousand controversial vaccines doses of AstraZeneca. The Cameroonian asked some questions which stay without an answer (i) how much times these vaccines can protect? (ii) does the cold chain can adequately permit the conservation of vaccines? (iii) don't we risk injecting Africans, the expired and poorly preserved vaccines? After the scandal of the management of covid-fund, it's a huge controversy on the false tests, particularly for the travelers which increase. The September month was partially murdered while the vaccination was hard to convince. At the national level, the total number of vaccinated people was less than 500.000. While waiting for people to be vaccinated, the received doses was expired. Only 4.910 doses of AstraZeneca vaccines on the 391.200 received doses were expired. The African cup of Nations (AFCON) had boosted the vaccina-

tion according to Mr. Georges Etoundi Mballa who is the director of the fight again the disease. The African Football Confederation (AFC) had forbidden access to stadiums to non-vaccinated people and Cameroonians were being vaccinated in order to see the AFCON live. On December 15, 2021, the CCOUSP (Centre de Coordination des operations d'urgences de Santé Publiques) in his situation "report number 106 of December 2021 globally estimated that the pandemic is under control, none of the health districts was on resurgence". At the end of December month, the 2021 AFCON permitted the Government to import million of new doses. Due to the AFCON, the total number of vaccinated people increased and reached a million persons. On mars 9, 2022 it was 1.074.824. On April 2022, the Government announced the end of free tests for COVID-19. According to the message of the general secretary of the presidency of the republic reverberating ''the high instruction" of the head of state, the Covid test will now cost 30.000 Franc CFA (50 USD).

3.7. Analysis of COVID-19 data of Zambia

4. Discussion

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5. Conclusion

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Credit Author Statement

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