Heterogeneous Severity of COVID-19 in African Countries: A Modeling Approach

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Abstract

Background: The COVID-19 pandemic has caused tremendous impact on global health and economics. The impact in African countries has not been investigated through fitting epidemic model to the reported COVID-19 deaths.

Method: We downloaded data for the twelve most-affected countries with the highest cumulative COVID-19 deaths to estimate the time-varying effective reproduction number ($R_0(t)$) and infection attack rate (IAR). We developed a simple epidemic model and fitted the model to reported COVID-19 deaths in 12 African countries, using iterated filtering and allowing flexible transmission rate.

Results: We found high heterogeneity in the case-fatality rate across countries, which may be due to different reporting or testing efforts. We found that South Africa, Tunisia, and Libya were hit hardest with a relatively higher $R_0(t)$ and infection attack rate

Conclusion: To effectively control the spread of COVID-19 epidemics in Africa, there is a need to consider other mitigation strategies (such as improvement in socio-economic wellbeing, health care system, water supply, awareness campaigns).

Keywords: SARS-CoV-2, pandemic, reproduction number, attack rate, seroprevalence.

1. Introduction

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a novel strain of coronavirus which has caused the current pandemic of the coronavirus disease 2019 (COVID-19) and has hugely affected all the six major regions of the world. Africa reported its first case of COVID-19 on 14 February 2020 in Cairo, Egypt (1-4). Since then the disease has spread across Africa, epi-centred in South Africa, and after a year (i.e., by 14 February 2021) over 2.7 million people have been infected including 68 thousand related deaths (1, 2, 5). The disease caused by SARS-CoV-2 emerged in China at the end of 2019 and has so far affected more than 116 million individuals and killed over 2.5 million people globally (1). COVID-19 shows a faster spreading ability than other coronaviruses of the same family (i.e., SARS-CoV and MERS-CoV) (3, 6-9). COVID-19 has also destructed the already overstretched health care system and weakened the socio-economic sector worldwide.

At the early phase of the epidemics, the twelve most-affected African countries with COVID-19 deaths were classified into three clusters/groups based on their similarity in exposure risk that originated from three Chinese provinces, namely Guangdong, Fujian, and Beijing that represent three different levels of risks of importation (high, medium and relatively low) (3). Each group corresponds to different Chinese airports in the associated province as the main sources of entry risk. Egypt, Algeria, and South Africa were identified as the highest importation risk group with moderate to high magnitude to the high epidemic response, followed by Nigeria, Ethiopia, Sudan, Morocco, and Kenya that were classified as moderate importation risk group with variable magnitude to response to epidemics with high vulnerability. The last group includes Tunisia, Cameroon, and Zambia and is classified as relatively low importation risk with variable magnitude to respond to epidemics with high vulnerability (2, 3).

With vaccines being developed recently, many of them are still in clinical trials, and some are already in the market for use against COVID-19 infection https://biorender.com/covid-vaccine-tracker (May have this link as a reference). Non-pharmaceutical interventions (NPIs) (which include social distancing, use of facemask, total or partial lockdown, contact tracing, quarantine, and isolation) are currently the main strategies to mitigate/prevent the spread of COVID-19 and has helped significantly in reducing (especially) the mortality rate across the globe (1, 10, 11).

Epidemiological modelling studies have long been used to understand and shed light on the transmission and spread of infectious diseases including the COVID-19 (e.g., see 3, 4, 12-14 and the references therein). A recent study by Uyoga et al. (15) described/examined the seroprevalence of anti-SARS-CoV-2 immunoglobulin G antibodies among Kenyan blood donors to find the extent to which the COVID-19 spread in community. They found that the crude seroprevalence (i.e., amount of SARS-CoV-2 pathogen in blood serum) was estimated at 5.6%, which indicates that SARS-CoV-2 exposure is more extensive than indicated by case-based surveillance. Another work (in preprint by the submission date of this manuscript) by Sykes et al. (43) study and examined the seroprevalence of SARS-CoV-2 among blood donors in South Africa. The results showed that SARS-CoV-2 prevalence differs by race groups and provinces, with seroprevalence among black donors higher than that of white donors, and other main population sub-groups. Their estimation of the seroprevalence (crudely equals the infection attack rate if we ignore the sero-reversion) in each of the four cities of the study area was Eastern Cape 62.5

(95% CI: 58.9 – 66.1); Northern Cape 31.8 (95% CI: 25.3 – 38.3); Free State 45.5 (95% CI: 39.9 - 51.1); and KwaZhulu Natal 52.1 (95% CI: 49.1 – 55.2). These results significantly differed from the work of Uyoga et al. (15), in which the given estimates of the seroprevalence in South Africa (given by age group) ranges from 3.4 to 10.0 (95% CI: 1.6 to 19.5) and seems to be epidemiologically more reasonable. Thus, we observed that the pandemic of COVID-19 in Africa has not been described appropriately (44).

In this paper, we study the transmission dynamics of the SARS-CoV-2 in Africa. Some of the epidemiological characteristics, implementation, and implications of NPIs of SARS-CoV-2 in Africa will be discussed. In particular, $R_0(t)$ and IAR of COVID-19 for twelve most affected African countries that experienced COVID-19 related deaths will be estimated. This will provide some useful insights and suggest effective COVID-19 control measures in Africa. Owing to the fact that NPIs play a key role in the prevention and control of SARS-CoV-2 epidemic. However, African countries have some difficulties, especially with regard to the compliance of the NPIs. Thus, we report/highlight some important factors that should be emphasized/improved to effectively control the spread of the disease. Simulations have shown the estimated values of $R_0(t)$ and IAR for the top twelve countries with COVID-19 related-deaths in Africa, which are vital epidemiological parameters to curtail the spread of COVID-19 in Africa and beyond.

2. Material and Methods

2.1. COVID-19 epidemic data

A set of COVID-19 observations indexed and arranged in time (16) for cases and deaths were extracted from the public domain of the World Health Organization (WHO) dashboard for disease surveillance reports of the twelve countries with most COVID-19 deaths in Africa (Zambia, Cameroon, Nigeria, Libya, Sudan, Kenya, Ethiopia, Algeria, Tunisia, Morocco, Egypt, and South Africa), retrieved from https://covid19.who.int/ (1). The time series distribution for the daily confirmations of COVID-19 cases and deaths for the twelve countries with high number of deaths in Africa by 12 February 2021 are visualized in **Figure 1**. This shows the trends of the epidemics. COVID-19 cases and deaths were represented by the black and red dotted curves, respectively. Based on the data scenarios, we observed that Libya showed the first wave of the epidemic. While other counties have shown at least two waves of the COVID-19 epidemic patterns with South Africa hit worst for both cases and deaths. The country's population data were obtained from the Worldometer, available via https://www.worldometers.info/population/.

2.2.The SEIHRD epidemic model

A Susceptible-Exposed-Infectious-Hospitalized-Removed-Dead (SEIHRD) model was proposed based on the classic SEIR-type (14, 17-19) to obtain the fitting results with biologically reasonable parameter values. The model was fitted to the deaths data to visualize the COVID-19 scenario in 12 most affected countries with COVID-19 deaths in Africa in order to give hint on the suitable NPIs that could appropriately and timely help to curtail the outbreaks with much reduced socio-economic consequences. In the classic SEIR-type of models, the population is sub-divided into four different compartments according to the infection status, representing susceptible (S), exposed (E), infectious (I), and recovered (R), respectively.

Based on the general epidemiological features of SARS-CoV-2 (12, 13), we considered two additional compartments for the infected individuals, which are hospitalized infected and dead compartment represented by H and D, respectively. Susceptible individuals can become exposed after getting contact with infected people. Exposed individuals can progress to the infectious compartment after the latency period. Infectious individuals can move to the hospitalized compartment which comes from either mild or severe cases. The infectious individuals can become recovered/removed following effective treatment (or naturally) or die due to the infection and enter the D compartment. The proposed model represented by the following non-linear ordinary differential equations is presented below.

$$\dot{S} = -\frac{\beta SI}{N},$$

$$\dot{E} = \frac{\beta SI}{N} - \sigma E,$$

$$\dot{I} = \sigma E - \gamma I,$$

$$\dot{H} = \rho\psi I - \xi H,$$

$$\dot{D} = \rho\xi H,$$

$$\dot{R} = (1-\rho)\gamma I + (1-\rho)\xi H.$$

Here, parameter β represents the flexible time-varying transmission rate, while parameter σ denotes disease progression rate from the latent stage to the infection's status. Parameter γ measures the rate at which individuals moves from I to H or R, while the parameter ξ represents the SARS-CoV-2-induced death rate from the H compartment.

In this model, the parameter ρ represents both the proportion-of hospitalization among infection and the proportion of death among hospitalization. Note that, hospitalization can be interpreted as symptomatic cases. Thus, the infection fatality rate is given by ρ^2. We fitted the weekly integrated D to the reported mortality data for each of the twelve countries with high number of COVID-19 related-deaths in Africa. The major assumptions include a negative binominal measurement noise in reporting with an over-dispersion parameter ϕ; a time-varying transmission rate (β), which is an exponential cubic spline function with 7 nodes.

The effective basic reproduction number $R_0(t)$ is given by $R_0(t) \approx \beta(t)/\gamma$. For more details regarding the model fitting process, see (14, 17-19). The iterated filtering algorithms is used to fit the model with an additional death class to the reported COVID-19 deaths for the twelve countries with most deaths in Africa to quantify the epidemics scenarios in Africa using the estimate of reproduction number. Thus, the proposed model was fitted to the SARS-CoC-2 mortality data for each of the twelve African countries.

3. Results

In **Figure 2** and **Figure 3**, we used the proposed SEIHRD model to simulate the COVID-19 mortality datasets (weekly) for the twelve African countries with the most COVID-19 deaths to explore the dynamic characteristics of the SARS-CoV-2 in Africa. The fitting results are used to estimate the time-varying effective reproduction number, $R_0(t)$, and the infection attack rate, IAR, for each of the twelve countries as depicted in **Figure 2** and **Figure 3**, respectively. **Figure 2** shows the fitting results of nine of the twelve countries with most COVID-19 deaths (Algeria, Cameroon, Egypt, Ethiopia, Kenya, Morocco, Libya, Nigeria, Sudan, Tunisia, and Zambia) which hid milder or with a relatively lower reporting rate. **Figure 3** shows the fitting results of three of the twelve countries with most COVID-19 deaths (Libya, South Africa, and Tunisia) which hit harder or with a relatively higher reporting rate. The weekly confirmed death was represented by the red circle, with the black curve representing the simulation medium, and the gray shaded region representing the 95% confidence interval (CI). We observed that by February 2021, Cameroon, Sudan, Algeria, and Tunisia are witnessing the third wave of the COVID-19 epidemics, whereas Zambia, Nigeria, Libya, Kenya, Ethiopia, Morocco, Egypt, and South Africa are observing the second wave of the SRAS-CoV-2 epidemics. The increase in transmission rate in these countries were likely due to the incompliance (or partial compliance) of the NPIs, age factor (proportion of the elderly population), seasonality, or behavioral changes (see, for instance (20)).

In **Table 1**, we obtained estimated values of the SARS-CoV-2 infection attack rate (IAR, the ratio of mortality per case in a particular population) for the twelve countries with the most deaths in Africa by February 2021. Our results showed that South Africa was hit hardest with an IAR of 0.414 followed by Tunisia with an IAR of 0.213 and then Libya with an IAR of 0.155, while Cameroon and Algeria hit mildest with an IAR of 0.022 and 0.042, respectively. These results indicate the impacts of the NPIs, and thus highlight the imperative need to implement other control strategies to mitigate the epidemics in Africa and beyond. Furthermore, we assumed that ρ varies from 0.01 to 0.1, thus the infection fatality rate varies between 0.0001 and 0.01. We presume the reported COVID-19 deaths are relatively reliable.

In Appendix Table 1**,** we reported the COVID-19 index case(s) scenarios for the twelve countries with the most deaths in Africa. We observed that SARS-CoV-2 was firstly reported in Egypt on 14 February 2020, and later followed by exponentially growing cases that spread in all parts of Africa, with South Africa as the epicenter until currently. Consequently, the estimated seroprevalences of SARS-COV-2 (i.e., estimated proportion of individuals in a population who test positive for COVID-19) were reported in Appendix Table 2, which shows that South Africa has an estimated seroprevalence of about 50% from blood donors (48). This result highlights that South Africa has hit harder which may be the consequence of the high proportion of mild or asymptomatic cases up to 80% of the total infection (49).

Appendix Table 3 presents the results of the estimated parameters of the model by employing the log-likelihood estimation technique. We found that South Africa, Egypt, and Tunisia have the log-likelihood values of -301.112, -263.928, and -232.474, respectively. These results indicate that South Africa has the highest transmissibly potential than other countries. In Appendix Table 4, we presented a summary of the estimated results of the time-varying transmission rate using a fixed number of nodes (n_m) as 7. Different values of the time-varying transmission rate were obtained based on the different simulation runs. The state values of the model were assigned with initial values given in Appendix Table 5.

4. Discussion: Implementation and Implications of NPIs

It has been more than a year since COVID-19 emerged in China and has spread very rapidly to over 200 countries and territories. Based on the lessons learned, African countries have slightly strengthened their preparedness plans against unexpected disease outbreaks such as the COVID-19 pandemic, which includes timely responses; airport surveillance and temperature screening at ports of entry; improvement in diagnostic centers for testing/mass testing; strengthened collaboration with other countries in other regions like China, United States of America and UK (for instance, deployment of medical personnel from the United Kingdom, donations of testing kits and PPEs by Jack Ma foundation, etc.) (2, 3). Africa was lucky to report its first case of COVID-19 at least a month after many countries in other continents had already reported thousands of cases and deaths (1, 6, 21), making the continent advantageous over others for timely preparations and responses to the pandemic in a variety of ways based on the lessons learned.

To visualize the actual scenario of the SARS-CoV-2 situation in twelve African countries with most deaths, we simulated the model using the weekly mortality data for each of the twelve countries to guide policy making for controlling the COVID-19 pandemic in Africa. To achieve reasonable fitting and estimates we make some assumptions, in particular, we divided these countries into two groups. Group 1) consists of South Africa, Libya, Tunisia, with a value of ρ above 0.045 (ie. IFR>0.2%). These countries reported more deaths per capita, which suggests a severe impact and/or efficient reporting of deaths, their IAR is 41.4%, 15.4%, and 8.6%, respectively. Group 2) consists of other nine countries (with a value of ρ between 0.01 and 0.04, ie. 0.01% < IFR < 0.16%) which shows mild impact and/or under-reporting of death. Their IAR varies between 2.2% to 20.2%, with a median of 5.7%. In **Figure 2** we depicted the time series fitting results of weekly reported COVID-19 deaths in nine of the twelve African countries (Algeria, Cameroon, Ethiopia, Kenya, Morocco, Nigeria, Sudan, and Zambia) which hit milder or with low reporting rate, and **Figure 3** shows the time series fitting results of weekly reported COVID-19 deaths in three of the twelve African countries (Libya, South Africa, and Tunisia) which hit harder or with a relatively higher reporting rate.

Based on recent reports in the literature, we highlighted that Africa's COVID-19 responses and control strategies were hugely not context-specific (15, 22). The responses and mitigation strategies via NPIs employed in Africa were described as replication or simply the COVID-19 *copy-and-paste* policy that was employed in other countries, such as China, the United Kingdom, and Europe, despite the variability in epidemiological characteristics, differences in weather and climate as well as different socio-economic growth level which probably impacts the transmission of the disease in Africa. Consistently, this *copy-and-paste* approach (also known as "*one-size-fit-all*" policy) is a bit more strenuous to properly implement and comply within Africa, and in fact, some of those stringent measures were obviously needless and turned out to be useless, causing more socio-economic hardships to many African countries. For instance, many African countries impulsively adopted the same lockdown policy together with other NPIs without the requisite knowledge of the COVID-19 features in Africa and the context-specific relevance and consequences of these measures to the community even at the early phase of the outbreaks (2).

Social distancing policy and restrictions of social gatherings (such as banning of weddings, religious activities, and funeral ceremonies) have been imposed to curtail the spread of the virus, even though it is almost practically impossible to comply with by many African countries. Mandatory wearing of facemasks in public places and the use of hand sanitizers were also a pervasive COVID-19 control measure in Africa, even though compliance is very difficult and problematic due to ignorance, poverty, resource constraints, and unawareness (2, 22). Although some successes have been achieved in respect of these response strategies, critics have described them as *one-size-fit-all* or *copy-and-paste* approach because of inappropriateness and unfavourability to local settings in Africa (23-25). Besides, one more important control measure is the school closure which had been massively criticized in Africa since many countries in the continent spontaneously closed down schools with the absence of exhaustive e-learning systems and inadequate infrastructure as has been practiced in other many countries (22).

Some of the main challenges regarding the fight against the COVID-19 pandemic in Africa include the imposition of the hand-hygiene policy when the majority of African population don't have access to adequate and portable water supply, temperature screening at the airports for travelers without considering asymptomatic carriers (asymptomatically infected people), the impossibility of work from home policy and insufficient quantity of PPEs especially for frontline health workers, insufficient data sharing and illegal crossing of borders at non-official points of entry (2, 26-28).

Food prices reported to have skyrocketed significantly in many countries in the continent during lockdowns due to panic buying and interruptions in the food supply chain within the community and between the countries (29). Although lockdowns have helped in controlling the spread of the disease, they (2, 22, 23) plunged millions of people into extreme poverty which likely has greater consequences and can kill more people than COVID-19 due to its negative impacts that have exhausted many people (22). Aside from the extreme poverty caused (likely) due to the effects of lockdowns, there were issues of human rights abuses by government officials or security agencies which add up to the hardship that has already emanated from the lockdowns policy in Africa (30).

Furthermore, another unexpected repercussion of the NPIs in Africa was the effect of the already fragile health care systems. Neglect of Neglecting the public health needs of populations in the wake of COVID-19 has already been reported with an unprecedented reduction in health service utilization causing more threats concerning other infectious diseases such as malaria, HIV/AIDS, Meningitis, etc. (31-33). Those implications may even cause the worse consequences during the post-COVID-19 pandemic because of their socio-economic destructions. We also observed that most of the top twelve African countries with most COVID-19 deaths reported their first COVID-19 case(s) between February and March 2020, see Appendix Table 1, which indicates that most of the stringency index policy turns out to be similar in most of the countries in Africa.

Conclusion

Overall, Africa has done remarkably well in terms of awareness and enlightenment campaigns by the media and civil society in disseminating health education and communication on COVID-19 prevention and control which helps in curtailing the spread of SARS-CoV-2 in the African region (2). Even though a more favorable/suitable policy needs to be considered, which can be implemented and can be complied easily by the general public to effectively control the spread of COVID-19 with much reduced economic hardships and negative consequences, especially during post-COVID-19 pandemic. With assumed range of infection fatality rate and flexible transmission rate, we model a unified simple model to the reported deaths in 12 African countries. The choice of group for countries was justified by the tests per capita performed across countries and the raw case-fatality rate across counties (Appendix Table 6). For instance, South Africa performed more tests per capita than other countries which implies a relatively higher reporting effort. The raw case fatality rate is high in South Africa. Combining these two aspects, we decide to allocate South Africa to high ρ group. Our fitting results reveals that South Africa, Libya, Tunisia, Ethiopia and Morocco were hit harder with SAR-CoV-2 epidemics in Africa. Thus, we suggested that there should be an imperative need to improve the socio-economic situation, quality water supply, as well as the health care system (which includes the provision of adequate health workers, PPEs, and test kits) in Africa to effectively and timely control the SARS-CoV-2 outbreaks.

In summary, we conducted a large-scale data analysis and modeling work of 12 African countries, and shed light on the possible infection fatality ratio and infection attack rate. We found large variation across countries, which could be due to different economic level, control measure and testing and report efforts. Our estimated infection attack rates, which is based on assumed range of infection fatality rate, are largely in line with population level serological studies. Our work is of importance since it is the first large scale population level modeling work for these African countries. Along with population level serological studies, our work gave insight on the possible severity in these countries.

Declarations

Ethics approval and consent to participate

Ethical approval was not required.

Consent to publish

All authors read and revised the manuscript, and gave consent for publication.

Availability of data and materials

All data used are obtained from public domain available from https://covid19.who.int/.

Competing interests

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Authors' contributions

Conceptualization: SSM & DH; Formal analysis: SSM, SZ, XW, NH, WW and DH; Writing – original draft: SSM, SZ, XW, NH, WW and DH; Writing – review & editing: SL and DH.

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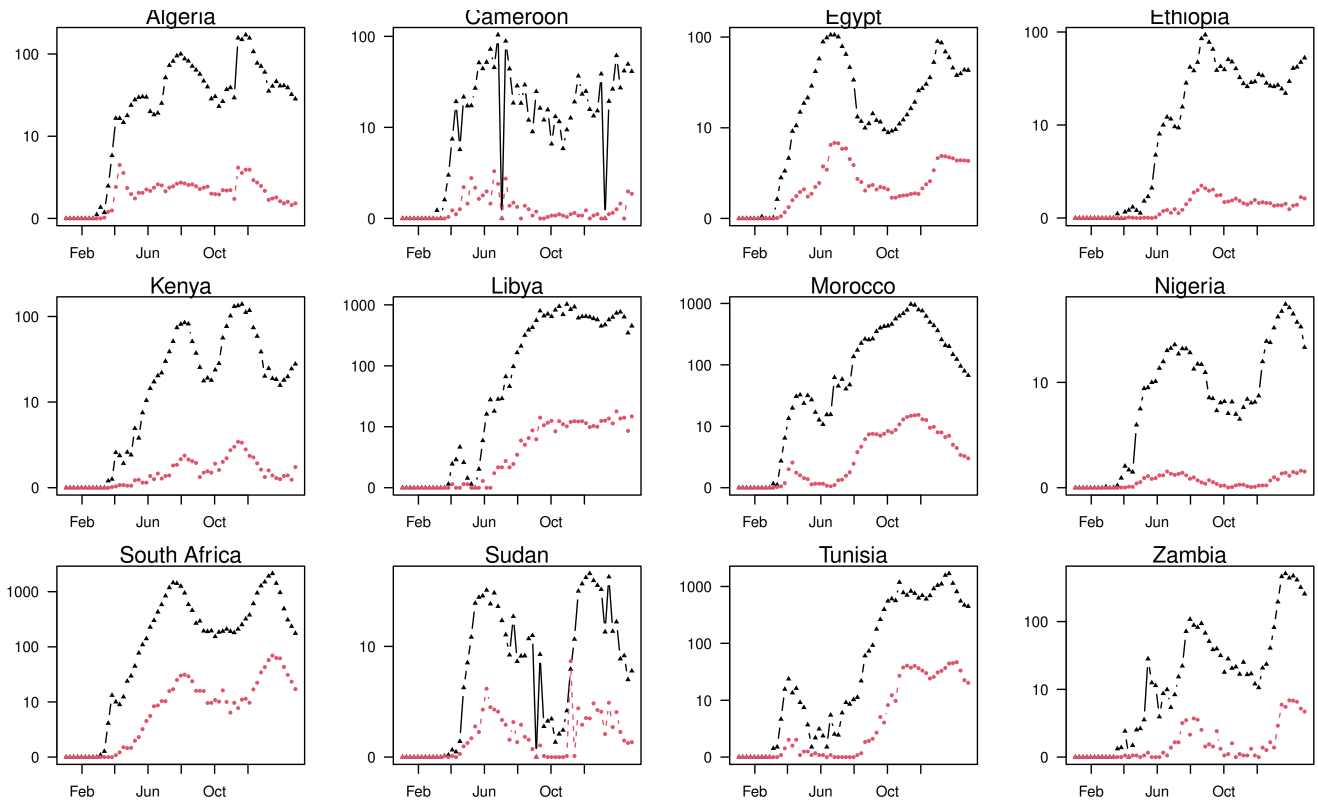


Figure 1: Daily confirmed cases (in black triangles) and deaths (in red tringles) of COVID-19 in twelve African countries with most COVID-19 deaths cases (population standardized, cases and deaths per 1 million population).

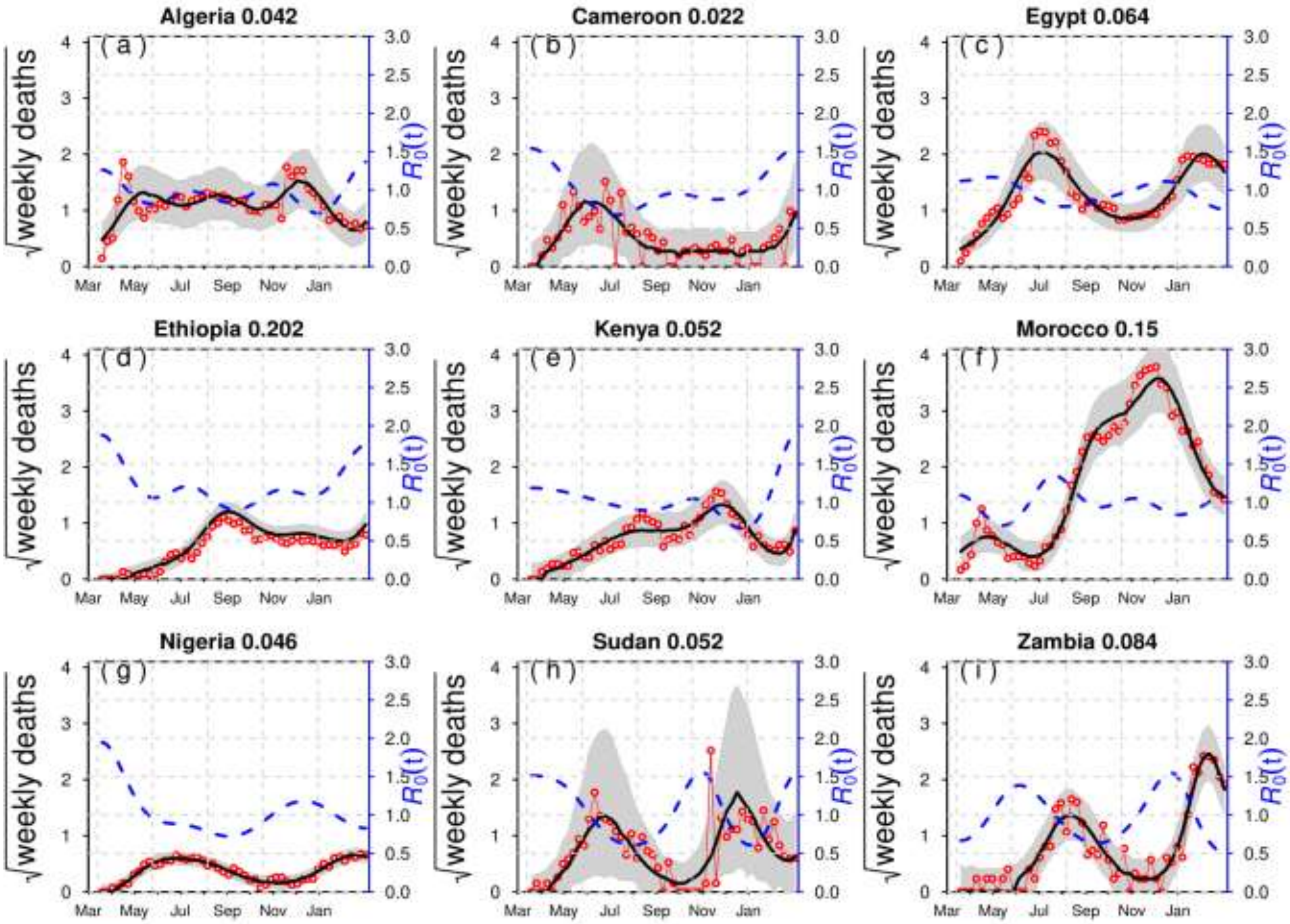


Figure 2: Time series fitting results of weekly confirmed COVID-19 deaths (in red circled) in nine of the twelve African countries with most COVID-19 deaths, which hit milder (with low reporting rate). Deaths are population standardized, i.e., deaths per 1 million population. The medium of the simulation is represented by the black curve, and the time varying effective reproduction number ($R_0(t)$) is denoted in blue dashed curve. The 95% confidence interval of the simulation is shown by the shaded (gray) region. The estimated IAR is shown in the title of each panel.

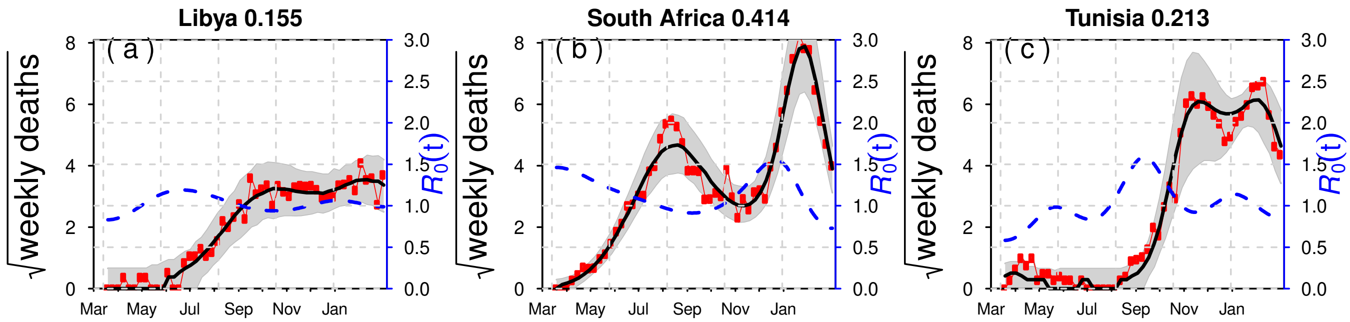


Figure 3: Time series fitting results of weekly confirmed COVID-19 deaths (in red circled) in three of the twelve African countries with most COVID-19 deaths, which hit harder (or with a relatively higher reporting effort). Deaths are population standardized, i.e., deaths per 1 million population. The medium of the simulation is represented by the black curve, and the time varying effective reproduction number ($R_0(t)$) is denoted in blue dashed curve. The 95% confidence interval of the simulation is shown by the shaded (gray) region. The estimated IAR is shown in the title of each panel.

***Table 1**:* Results of the infection attack rates (IAR) for the twelve African countries with the most COVID-19 deaths by the end of February 2021.

Country	Population size	Reported deaths	Est. Infection attack rate
Algeria	43851044	2973	0.042
Cameroon	26545863	523	0.022
Egypt	102334404	10541	0.064
Ethiopia	114963588	2321	0.202
Kenya	53771296	1847	0.052
Libya	6871292	2156	0.155
Morocco	36910560	8598	0.15
Nigeria	206139589	1891	0.046
South Africa	59308690	49667	0.414
Sudan	43849260	1880	0.052
Tunisia	11818619	7911	0.213
Zambia	18383955	1059	0.084

Appendices

Appendix Table 1: Index case(s) of COVID-19 for the top twelve African countries with the most COVID-19 deaths by February 2021.

Country	Case	Index case confirmation	Case history	References
Algeria	110049	25 Feb, 2020	Italian from Italy to Algeria	(34)
Cameroon	31394	6 Mar, 2020	French national from French to Yaounde’	(35)
Egypt	171993	14 Feb, 2020	Chinese from China to Egypt	(3)
Ethiopia	144862	13 Mar, 2020	Japanese from Japan Burkina Faso via Ethiopia	(34)
Kenya	102353	12 Mar, 2020	Kenyan from US to Kenya via UK	(36)
Libya	126361	24 Mar, 2020	Returned traveler from Saudi Arabia	(37)
Morocco	477160	2 Mar, 2020	Returned Moroccan from Italy	(38)
Nigeria	143561	27 Feb, 2020	Italian from Milan to Lagos	(39)
South Africa	1484900	5 Mar, 2020	Returned traveler from Italy	(33, 40)
Sudan	29952	13 Mar, 2020	Traveler from United Arab Emirates	(34)
Tunisia	220478	2 Mar, 2020	Returned Tunisian from Italy	(41)

Zambia	66598	18 Mar, 2020	Returned travelers from French via United Arab Emirates	(42)

Appendix Table 2: Summary table of the estimated seroprevalence of SARS-CoV-2 in twelve African countries with most deaths.

Country	Estimated Seroprevalence percentage (95% CI)	Refs
Algeria	Na	
Cameroon	Na	
Egypt	4.4 (3.6 - 5.3)	(45)
Ethiopia	3	(44)
Kenya	4.3 (2.9 – 5.8)	(15)
Libya	2.74	(46)
Morocco	Na	
Nigeria	45.1 (in frontline health-care workers)	(44, 47)
South Africa	47.975 (43.3 – 52.675)	(43)
Sudan	Na	
Zambia	Na	

***Appendix Table 3**:* Parameter setting and estimates log likelihood.

Country	*loglik*	*loglik.sd*	σ	ρ	γ	ξ	*Population*
Algeria	-224.253	0.029	182.5	0.04	121.667	30.42	43851044
Cameroon	-144.127	0.039	182.5	0.03	121.667	30.42	26545863
Egypt	-263.928	0.057	182.5	0.04	121.667	30.42	102334404
Ethiopia	-163.456	0.121	182.5	0.01	121.667	30.42	114963588
Kenya	-180.626	0.032	182.5	0.026	121.667	30.42	53771296
Libya	-152.392	0.129	182.5	0.045	121.667	30.42	6871292
Morocco	-228.438	0.086	182.5	0.039	121.667	30.42	36910560
Nigeria	-169.985	0.07	182.5	0.014	121.667	30.42	206139589
South.Africa	-301.112	0.052	182.5	0.045	121.667	30.42	59308690
Sudan	-204.765	0.019	182.5	0.027	121.667	30.42	43849260
Tunisia	-232.474	7.476	182.5	0.088	121.667	30.42	11818619
Zambia	-146.848	0.091	182.5	0.026	121.667	30.42	18383955

***Appendix Table 4**:* Estimates of node values of the time varying transmission rate.

Country	n_m	*log.beta*	*log.beta1*	*log.beta2*	*log.beta3*	*log.beta4*	*log.beta5*	*log.beta6*
Algeria	7	5.0085	4.618	4.7797	4.6275	4.8575	4.4571	5.0695
Cameroon	7	5.233	4.8013	4.4089	4.7312	4.6758	4.8319	5.2296
Egypt	7	4.9114	4.933	4.5948	4.6307	4.8223	4.8586	4.5068
Ethiopia	7	5.4317	4.8883	4.9975	4.6998	4.9516	4.9207	5.3602
Kenya	7	4.9747	4.9008	4.7466	4.724	4.7922	4.433	5.4337
Libya	7	4.6074	4.8976	4.9502	4.7852	4.7528	4.8624	4.7877
Morocco	7	4.8897	4.448	5.0903	4.7568	4.8531	4.627	4.8797
Nigeria	7	5.4681	4.8345	4.6533	4.4809	4.8602	4.9109	4.6148
South.Africa	7	5.191	5.0202	4.8431	4.7073	4.9659	5.1832	4.4887
Sudan	7	5.2186	5.0223	4.3629	4.619	5.2147	4.331	5.1936
Tunisia	7	4.5318	4.4076	4.6533	5.3055	4.6676	4.8369	4.4059
Zambia	7	4.3986	5.0439	4.8931	4.3508	4.7816	5.1662	4.1408

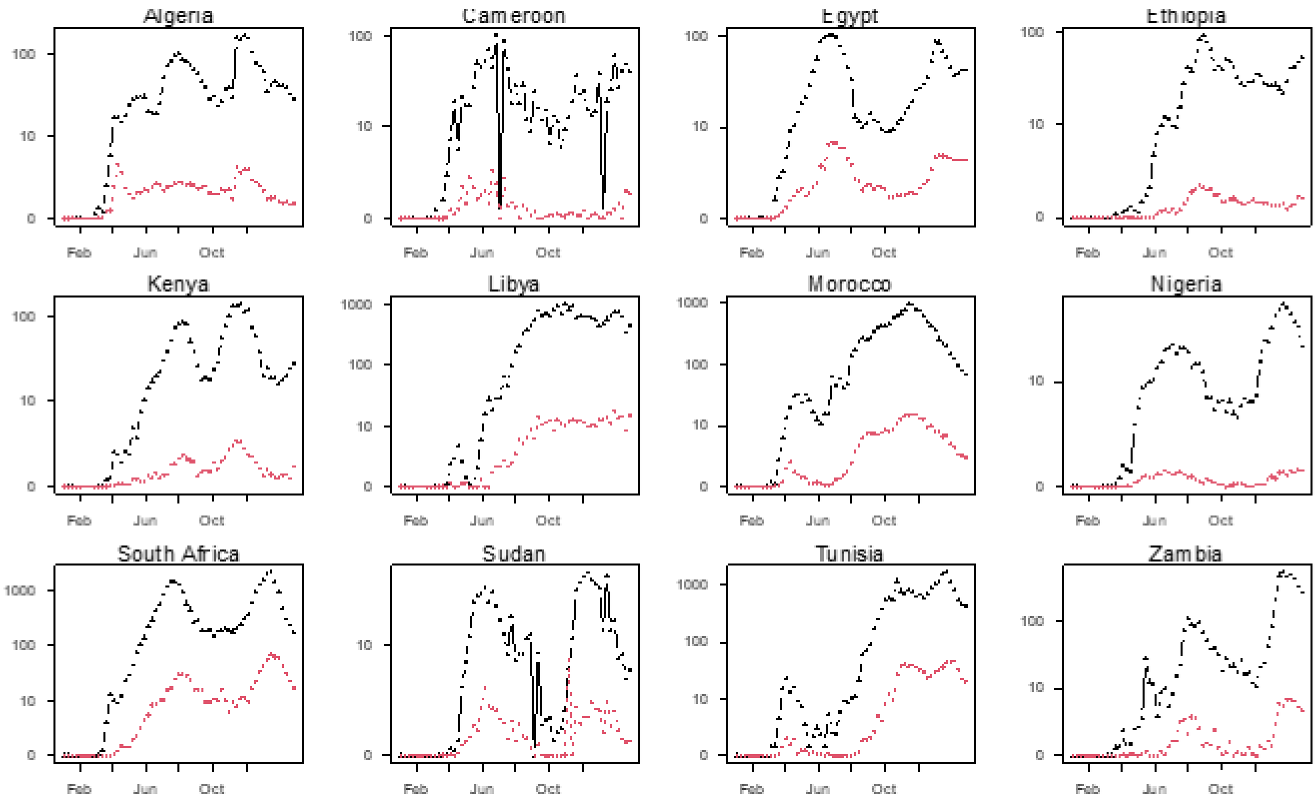
Appendix Table 5: Estimated initial values of state variable of the model.

Country	ϕ	$S(0)$	$E(0)$	$I(0)$	$H(0)$	$D(0)$	$R(0)$
Algeria	0.1036	41658492	5047	5047	505	50	2181902
Cameroon	0.4824	25218570	392	392	39	4	1326467
Egypt	0.0597	97217684	4318	4318	432	43	5107609
Ethiopia	0.0015	109215409	125	125	12	1	5747916
Kenya	0.0601	51082731	494	494	49	5	2687521
Libya	0.0063	6527727	117	117	12	1	343317
Morocco	0.0236	35065032	3765	3765	376	38	1837584
Nigeria	0.0048	195832610	506	506	51	5	10305912
South.Africa	0.0389	56343255	271	271	27	3	2964864
Sudan	0.8388	41656797	186	186	19	2	2192070
Tunisia	0.0001	11227688	569	569	57	6	589730
Zambia	0.0055	17464757	423	423	42	4	918305

Appendix Table 6: Reported cases and tests. Data from https://www.worldometers.info/ by March 7, 2021.

Country	Reported cases	Test performed	Test per 1m population	Positive rate (per test)	Raw case-fatality rate
Algeria	114234	NA	NA	NA	0.0264
Cameroon	35714	905000	33529	0.0395	0.0154
Egypt	186503	1e+06	9649	0.1865	0.059
Ethiopia	166138	2178403	18637	0.0763	0.0146
Kenya	108827	1333690	24439	0.0816	0.0172
Libya	138640	752060	108448	0.1843	0.0164
Morocco	486223	5729423	153984	0.0849	0.0179
Nigeria	158506	1580442	7541	0.1003	0.0124
South Africa	1521068	9255492	154731	0.1643	0.0333
Sudan	28605	NA	NA	NA	0.0662
Tunisia	237704	1004877	84424	0.2366	0.0345
Zambia	82421	1131606	60414	0.0728	0.0136

Figures



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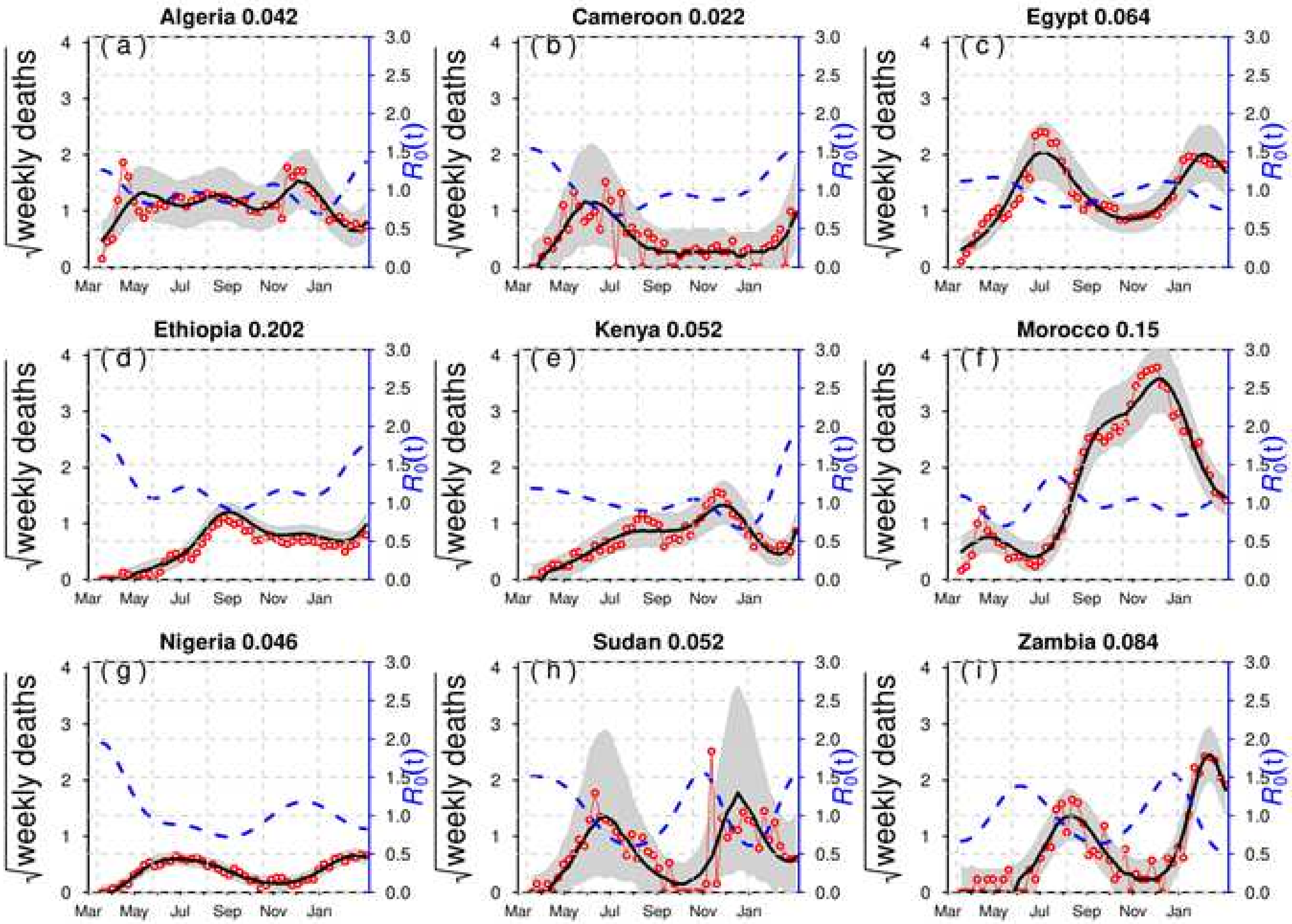

Figure 2

Time series fitting results of weekly confirmed COVID-19 deaths (in red circled) in nine of the twelve African countries with most COVID-19 deaths, which hit milder (with low reporting rate). Deaths are population standardized, i.e., deaths per 1 million population. The medium of the simulation is represented by the black curve, and the time varying effective reproduction number (R_0 (t)) is denoted in blue dashed curve. The 95% confidence interval of the simulation is shown by the shaded (gray) region. The estimated IAR is shown in the title of each panel.

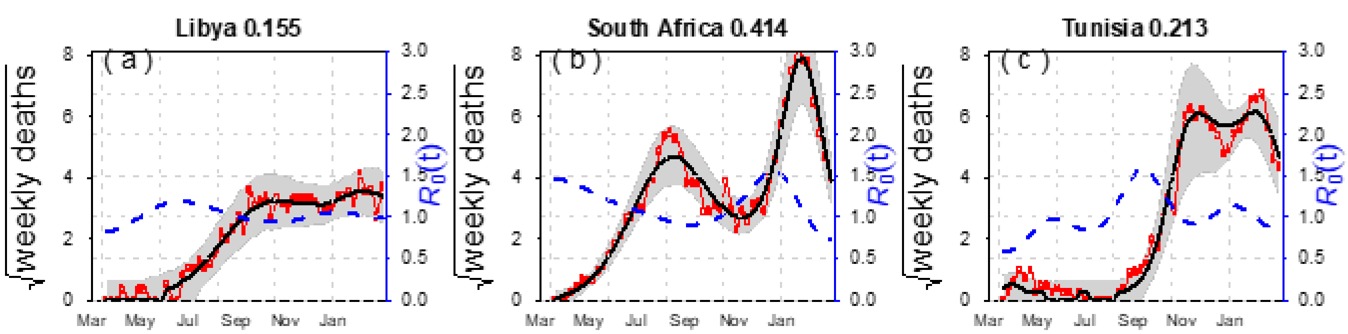

Figure 3

Time series fitting results of weekly confirmed COVID-19 deaths (in red circled) in three of the twelve African countries with most COVID-19 deaths, which hit harder (or with a relatively higher reporting effort). Deaths are population standardized, i.e., deaths per 1 million population. The medium of the simulation is represented by the black curve, and the time varying effective reproduction number ($R_0(t)$) is denoted in blue dashed curve. The 95% confidence interval of the simulation is shown by the shaded (gray) region. The estimated IAR is shown in the title of each panel.