Journal Pre-proof

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PII: S1201-9712(22)00071-6
DOI: https://doi.org/10.1016/j.ijid.2022.01.062
Reference: IJID 5984

To appear in: *International Journal of Infectious Diseases*

Received date: 9 August 2021
Revised date: 2 January 2022
Accepted date: 27 January 2022

Please cite this article as: Manar Marzouk , Omar Alrashid Alhiraki , Ricardo Aguas , Bo Gao , Hannah Clapham , Wael Obaid , Hani Altaleb , Naser Almhawish , Hazem Rihawi , Aula Abbara , Yazan Douedari , Mahmoud Hariri , Natasha Howard , in collaboration with the CoMo Consortium, SARS-CoV-2 transmission in opposition-controlled Northwest Syria: modelling pandemic responses during political conflict, *International Journal of Infectious Diseases* (2022), doi: https://doi.org/10.1016/j.ijid.2022.01.062

Highlights

- A first COVID-19 model for Northwest Syria using a participatory approach.
- A second COVID-19 wave is likely if only 20% of the population is vaccinated.
- A more transmissible variant could double the death toll and cause a second wave.
- Vaccinating 60% of the population by June 2022 could stop COVID-19 transmission.
- Decision-makers should urgently increase COVID-19 vaccination coverage.

SARS-CoV-2 transmission in opposition-controlled Northwest Syria: modelling pandemic responses during political conflict

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Word count: Abstract: 292/300; Body: 4,318/5,000

Keywords: modelling; COVID-19; vaccination; non-pharmaceutical interventions; Syria

ABSTRACT

Introduction

Ten years of conflict has displaced more than half of Northwest Syria's (NWS) population and decimated the health system, water and sanitation, and public health infrastructure vital for infectious disease control. The first NWS COVID-19 case was declared 9 July 2020, but impact estimations in this region are minimal. With the rollout of vaccination and emergence of the B.1.617.2 (Delta) variant, we aimed to estimate COVID-19 trajectory in NWS and potential effects of vaccine coverage and hospital occupancy.

Methods

We conducted a mixed-method study, primarily including modelling projections of COVID-19 transmission scenarios with vaccination strategies using an age-structured, compartmental susceptible-exposed-infectious-recovered (SEIR) model, supported by data from 20 semi-structured interviews with frontline health-workers to help contextualise interpretation of modelling results.

Results

Modelling suggested that existing low stringency non-pharmaceutical interventions (NPIs) minimally affected COVID-19 transmission. Maintaining existing NPIs after Delta variant introduction is predicted to result in a second COVID-19 wave overwhelming hospital capacity and resulting in a 4-fold increased death toll. Simulations with up to 60% vaccination coverage by June 2022 predict a second wave is not preventable with current NPIs. However, 60% vaccination coverage by June 2022 combined with 50% coverage of mask-wearing and handwashing should reduce the number of hospital beds and ventilators needed below current capacity levels. In the worst-case scenario of a more transmissible and lethal variant emerging by January 2022, a third wave is predicted.

Conclusion

Total COVID-19 attributable deaths are expected to remain relatively low, due largely to a young population. Given the negative socioeconomic consequences of restrictive NPIs, such as border or school-closures for an already deeply challenged population and their relative ineffectiveness in this

context, policymakers and international partners should instead focus on increasing COVID-19 vaccination coverage as rapidly as possible and encouraging mask-wearing.

INTRODUCTION

Syrian conflict and COVID-19 in Northwest Syria

Ten years into Syria's protracted and violent conflict, more than half the 22 million pre-war population has been displaced and more than half a million civilians have been killed, including more than 900 health-workers (UNOCHA, 2020, Fouad et al., 2017). The conflict has decimated the health system, water and sanitation infrastructure, and public health infrastructure crucial for managing infectious diseases. Northwest Syria (NWS), a 2,460 square-kilometre territory bordered by Turkey on one side and government-controlled areas on the other, has an estimated population of 4.2 million plus hosting approximately 2.6 million internally-displaced people around 1.2 million of whom live in camps (Global Shelter Cluster, 2021). Average population density is 800 per square kilometre, but exceeds 5,100 per square kilometre in Al Dana displacement camp, increasing the risk of infectious disease transmission (REACH, 2020). On 9 July 2020, the Assistance Coordination Unit/Early Warning Alert and Response Network (ACU/EWARN) announced the first confirmed COVID-19 case in NWS, a 39 year-old doctor, with 4 July reported as date of onset (WHO, 2021a). As of 26 May 2021, EWARN confirmed 23,072 cases and 83 deaths, both of which have increased in subsequent months (Assistance Coordination Unit, 2021).

Of many COVID-19 transmission and response risks in NWS, the greatest may be fragmented health system governance and policymaking, which means no single institution can enforce COVID-19 mitigation measures (Douedari and Howard, 2019). Four key actors help coordinate the COVID-19 response in NWS, including the World Health Organization (WHO)-led COVID-19 Taskforce, the Syrian Interim Government (SIG)-led COVID-19 National Response Team, de-facto authorities in Idlib, and

Turkish-supported local councils in northern Aleppo. This affects COVID-19 response coordination and implementation of non-pharmaceutical interventions (NPIs) in NWS. While age is a major risk factor for COVID-19, its impact on severity and mortality in Syria may be lower given the relatively young population. Other risks in NWS that likely affect local epidemic trajectory, include: (i) transmission risks due to high population densities and overcrowding in displacement settings, where large multi-generational households are common; (ii) poor water, sanitation and hygiene (WASH) infrastructure in NWS's 43 sub-districts; and (iii) limited treatment due to poor health system capacity, with total numbers of hospital beds, Intensive Care Units (ICU) beds, and ventilators of 370, 137, and 131 respectively. This is three times less than the minimum Sphere guidelines requirement of 6.1 inpatient beds per 10,000 persons (Sphere, 2018). In May 2021, AstraZeneca vaccine was rolled out in NWS through COVAX, to initially cover 2% then 20% of the population, primarily health-workers and those with comorbidities (WHO, 2021b, Sphere, 2018, World Health Organisation, 2021a, Health Cluster Turkey Hub, 2021, World Health Organisation, 2021b).

SARS-CoV-2 surveillance and epidemiology in NWS

ACU/EWARN expanded surveillance to include COVID-19, providing daily and weekly reports. During initial pandemic preparations in spring 2020, ACU/EWARN had only one testing machine with a limited daily capacity of approximately 180 tests. Testing capacity expansion in May-September included three laboratories equipped with a total of four PCR machines, more staff trained in laboratory testing, and resources allocated to purchasing diagnostics, providing total capacity of over 1,500 tests daily. WHO case definitions were used, combining clinical, epidemiological, and laboratory criteria (UNOCHA, 2021). Laboratory positivity rates varied from approximately 3% in the early stages of the pandemic to 40% at the peak of the first wave. ACU/EWARN commenced contact tracing from the first COVID-19 case on 9 July 2020, to help contain circulation and initiate isolation of cases and contacts. While this helped limit the number of cases from the first detected cluster, other clusters appeared and the situation quickly changed from multiple clusters to community transmission. Thus, COVID-19 transmission and relevant mitigation initiatives should be considered within NWS socioeconomic realities and health system capacities (Douedari et al., 2020).

Objectives

This study aimed to model five COVID-19 trajectory scenarios in NWS and explore potential explanations for the relatively low numbers of reported cases and deaths during the first wave. Objectives were to: (i) estimate numbers of cases, hospital occupancy, and deaths if four of current NPIs were released for twelve months without the emergence or introduction of a variant of concern (VOC); (ii) explore interpretation and contextualisation of modelling results through interviewing frontline health-workers; and (iii) estimate numbers of cases, hospital occupancy, and deaths after the SARS-CoV-2 B.1.617.2 (Delta) variant emerges, and varying vaccination coverages are achieved.

METHODS

Study design

We conducted a mixed-method study, with modelling projections of COVID-19 transmission scenarios supported by semi-structured interviews with frontline health-workers.

Modelling data collection and fitting

Model and data source

We used an age-structured, compartmental susceptible-exposed-infectious-recovered (SEIR) model, developed by the COVID-19 International Modelling (CoMo) Consortium, and a participatory approach in engaging local policymakers throughout the modelling process (Aguas et al., 2020, Adib et al., 2021). EWARN/ACU provided the epidemiological dataset on 4 April 2021, which included daily case data (i.e. people tested positive), daily deaths (i.e. deaths within 28 days of positive test by date of death), and PCR test performance (i.e. daily number of people receiving a PCR test).

Correction of COVID-19 cases

Figure 1 shows a clear reliance of reported daily cases on underlying testing effort, which distorted the relative severity of the first wave. First, we control for the effect of daily testing capacity variation and testing effort changes in NWS on the reported daily case data, by applying a testing effort correction factor consisting of number of people PCR tested per day at the peak of the first wave in November 2020, i.e. 1,400 tests per day. Each day (*i*) we have: $corrected\_cases_i=(reported\_cases_i*1400)/PCR\_tests_i$). Then, we generated a time series of corrected case data (Figure 1a, right)**.** The raw case series showed no time delay between peaks in cases and in deaths, indicating potential under-reporting of cases when testing was low, while the corrected case series generated a more accurate mirroring of test positivity data.

Model fitting

Parameter estimation was performed using a particle-filtering approach through the 'pomp' R package (King et al., 2016), and assuming the reported case and death data can be accurately described by a Poisson process. We tried to reproduce the dynamics of COVID-19 transmission in NWS by estimating the set of parameters *q* that maximises the log-likelihood (LL) of observing the daily numbers of reported deaths D and cases C:

$$LLd(\theta|D) = -\sum_{k=1}^{n} yd(k,\theta) + \left(\sum_{k=1}^{n} \tilde{y}d(k)\ \ln(yd(k,\theta))\right) - \sum_{k=1}^{n} \ln\big(\tilde{y}d(k)\big)\,!$$

$$LLc(\theta|C) = -\sum_{k=1}^{n} yc(k,\theta) + \left(\sum_{k=1}^{n} \widetilde{yc}(k)\ \ln(yc(k,\theta))\right) - \sum_{k=1}^{n} \ln\big(\tilde{y}c(k)\big)\,!$$

in which $yd(k,\theta)$ is the simulated model output number of COVID-19 deaths at day k; $yc(k,\theta)$ is the simulated model output number of COVID-19 cases at day k; n is the total number of days included in the analysis; and $\theta = \{p;\ st;\ I_0;\ sc\}$ is the set of parameters to estimate including: (*p*) probability of infection given contact; (*st*) start date of simulation; (I_0) number of infected individuals on the first day of simulation; and (*sc*) scaling factor for infection hospitalisation rate. Two measurements, i.e. daily mortality count (LLd) and daily case incidence count (LLc), are included in a weighted global function evaluating the model's probability density function: LL = LLd+LLc(max($\tilde{y}d$)/max($\tilde{y}c$)). The last term weighs the case incidence likelihood so as to have the same importance for the overall likelihood as the death incidence likelihood, and depends on the ratio between observed peak number of cases and observed peak number of deaths.

The remaining model parameters were taken from the literature whenever possible or customised to fit the NWS context using expert opinion and local data, including population profile, hospitalisation parameters, and efficacy and coverage of selected NPIs for each scenario. Apart from relevant peer-reviewed literature, parameters were based on Relief Experts Association (UDER) surveys, and expertise of Syrian public health professionals and policymakers, including Idleb Health Directorate, NWS Health Information System Unit, EWARN/ACU, NWS Syria Corona Awareness Team, NWS COVID-19 Taskforce, and COVID-19 National Response Team for NWS.

Figure 1b shows results of model fitting for our baseline scenario, using the following parameters: (i) estimated start date of simulation at 01 June 2020; (ii) assumed simulation end date of 30 June 2022; (iii) estimated probability of infection giving contact at 0.0127; (iv) assumed mean infection migrant per day of 0.01; (v) assumed percentage all asymptomatic infection reported at 0%; (vi) assumed percentage all symptomatic infection reported at 17%; (vii) estimated scaling factor for infection hospitalisation rate (IHR) at 2.102; and (viii) average duration of immunity at 1.5 year, as there is growing evidence suggesting previous exposure to SARS-CoV-2 does not guarantee total immunity (Tillett et al., 2021). We calculated uncertainties by running the model 100 times with a 10% gaussian noise on parameter values and depict the 95% credible intervals.

NPIs included in transmission scenarios

For scenario modelling, we defined *coverage* as “the proportion of people in the population adhering to interventions” and *efficacy* as “the relative change in risk of infection if adhering to the intervention.” NPIs implemented in NWS are: an international travel ban, handwashing, mask-wearing, safe-distancing, and school closures (Table 2 show the change of coverage in each scenario). We added vaccination as rollout began in May 2021.

1. *International travel ban*: movement was estimated at 5% pre-pandemic rates, as NWS international borders have been closed since March 2020, except for limited movement including official crossings, e.g. humanitarian and medical staff, traders, Turkish officials and military staff, and low-level smuggling activities between NWS and Northeast Syria or government-controlled Syria (Relief Experts Association, 2020).
2. *Handwashing:* coverage was estimated at 25%, based on an UDER survey of WASH access and handwashing practices in NWS and assumptions of improved hygiene practices due to COVID-19, e.g. frequent 20-second handwashing with water and soap and avoiding handshaking or touching mouth, nose, and eyes (Relief Experts Association, 2020).

3. *Mask-wearing*: coverage was estimated at 15%, based on an UDER survey of facemask use in NWS showing approximately 10% of the population reported mask-wearing in public and other data suggesting actual rates were nearer 5%(Relief Experts Association, 2020).
4. *Safe-distancing*: coverage was estimated at 5%, in discussion with local decision makers, as they estimated no more than 5% of the population adhered to restrictions on local gatherings and celebrations.
5. *School closures:* coverage was 80% in summer 2020, based on an UDER survey of community leaders, who postponed reopening for two weeks in September. Schools were then reopened with some modest interventions that rapidly reverted to normal practice (Relief Experts Association), 2020).
6. *Vaccination:* we assumed that AstraZeneca remains the main vaccine provided in NWS starting May 2021, with an observed efficacy of 74%, duration of efficacious period of 1.5 year, and vaccine coverage of 2% by September 2021, and 20% or 60% by June 2022 in accordance with NWS's approved application for COVAX support and in discussion with NWS policymakers (WHO, 2021b).

Modelling transmission scenarios

The baseline (current) scenario predicts the impact on COVID-19 trajectory of extending low coverage NPIs for 12 months with no VOC and 2% vaccination coverage.

Scenario 1 predicts the impact on COVID-19 trajectory of ending four existing NPIs (i.e. international travel ban, handwashing, mask-wearing, safe-distancing) with no COVID-19 VOC introduced for the next twelve months alongside 20% vaccination coverage. School closures were only for a week in November 2020 and three months June-August 2021, while vaccination coverage was assumed to be

2% by May 2021 and 20% by June 2022 (i.e. in accordance with planned vaccine rollout in NWS). The remaining parameters are kept the same as in the baseline scenario.

Scenario 2 predicts the impact on COVID-19 trajectory of introducing the SARS-CoV-2 B.1.617.2 (Delta) in July 2021. This has been done by adjusting four parameters: virus transmissibility, lethality, breakthrough infection probability and coverage of international travel ban. The latter was changed from 75 to 30 to allow for the entry of a new variant. Table 3 shows the coverage and duration of each of these parameters. The remaining calibration parameters were the same as for Scenario 1 with the same NPIs until 30 June 2022. We also included a worst-case scenario (2d) that enables some examination of the sensitivity of our model given limited evidence on the transmissibility, lethality, and breakthrough infection probability of the next VOC. We considered the worst-case scenario by increasing virus transmissibility, lethality and breakthrough infection probability to 2, 2, and 30 respectively.

Interview data collection and analysis

To aid interpretation, OAA and YD conducted 20 interviews with purposively recruited frontline health-workers at health facilities and COVID-19 treatment centres (Table 1). Inclusion criteria were: (i) living in NWS and involved in COVID-19 response; (ii) aged over 21; and (iii) able to speak Arabic or English. OAA and YD conducted interviews in Arabic using Zoom (Zoom Video Communications, Inc) or WhatsApp applications between March 2020 and May 2021. After providing informed consent, interviewees were asked about COVID-19 cases, responses, and issues. We analysed data thematically, using deductive and inductive manual coding as described by Braun & Clarke (Braun et al., 2019).

Patient and public engagement

We used a participatory approach in modelling by engaging NWS policymakers and practitioners from the start of this study. They contributed to study design, identifying relevant research questions and scenarios, analysis, and interpretation of data. Four who have been particularly active are included as co-authors.

RESULTS

Predicted COVID-19 under-reporting, transmission, and case fatality rates

Case correction and model fitting provided relatively low reporting, transmission, and case fatality rate estimates. Modelling estimated 47.5% of the NWS population would have been infected with SARS-CoV-2, with approximately 538 deaths, between 01 June 2020 and 26 May 2021. Only 1.2% population infection was reported to EWARN during the same period, though this only including symptomatic cases with no serology data available.

Modelling indicated the effective reproductive number (*Rt*) remained just below 1.5 during the first wave in July-November 2020, declined below 1 in December 2020, and increased to 1 by October 2021 (Figure 3a). Modelling also indicated a relatively low overall COVID-19 fatality rate, with a very low IFR for people younger than 45 years of age and a much higher fatality rate for older people. Figure 3b shows reported and predicted hazard ratios by NWS age group in years, indicating increased predicted fatality rates from age 35 with the most significant increases in both predicted and reported rates from age 65.

Qualitative explanations on under-reporting

To explore the lower reported than predicted death rates, we asked frontline health-workers for their perspectives. Most health-workers suggested some under-reporting of COVID-19 deaths was due to limited testing capacity, poor data management, and lack of coordination between public and private health sectors in NWS.

> *'There are many cases that have been treated in private hospitals, which consider out of the NWS health system coverage and do not share its health records.'* (HCW4)

Others reported that patients with severe symptoms were hesitant to be admitted to hospitals, preferring to be treated at home, and so were never registered or included in case data.

> *'The majority of people with severe cases refused the hospitalization and demanded to be treated at home. This might be diminished the probability of being exposed to secondary hospital infections by antibiotic-resistant bacteria and decrease the case fatality rate.'* (HCW2)

Qualitative perspectives on low transmission

Health-workers proposed several theories for the relatively low COVID-19 transmission noted in NWS. A common theory was that so many had died already that those left were more able to resist infection. Another related it to the lack of insulated shelter for internally-displaced families, representing over half the NWS population, which may have had a positive unintended consequence of allowing constant airflow.

> *'The low infection rate in the camps might be explained by the nature of the tents that are torn and always open to the airflow. Furthermore, the desperate uninhabitable condition except for youth, in which elderly die due to NCDs.'* (HCW6)

Another theory was that relatively low COVID-19 transmission during winter could be related to communal behaviour in NWS, given few public activities and constant electricity cuts had imposed an informal form of curfew that may have reduced transmission temporarily.

> ‘*Unlike other countries, the winter season has had a relatively positive role regarding COVID-19 pandemic in NWS. Due to the lack of electricity and the early sunset, something comparable to the curfew happens every day for 14 hours until morning, as well as a significant reduction in socialising. However, this shifting is relative. The next morning, overcrowding in schools, markets, bakeries and camps is noticed*.’ (HCW2)

Some interviewees highlighted increased public adherence to prevention measures after confirmation of the first COVID-19 case in the area and potential effects this had on reducing transmission. Additionally, one interviewee suggested women were more protected from COVID-19 in public spaces, as due to conservative NWS social norms many women wore niqab, which covered their mouth and nose.

> *‘Patterns of the veil of women in NWS might have an essential role similar to the face-masks. Almost 30% of women wear the niqab as a religious habit.’* (HCW1)

Qualitative suggestions on low case fatality rate

Health-workers suggested that low case fatality rates could be due to natural or cross-immunity from other infections or vaccination.

> *‘NWS population might have unique characteristics such as low median age, strong immunity due to previous infections since childhood, multiple vaccines administered, vegetable diet, and rural lifestyle in general.’* (HCW5)

COVID-19 transmission scenarios

Scenario 1. Ending low-coverage NPIs with no VOC and 20% vaccination coverage

This transmission scenario predicted 48.9% of the NWS population would be infected with SARS-CoV-2 by 30 June 2022, with 550 cumulative attributable deaths, and *Rt* remained below 1 between November 2020 and August 2021, then reached 1 by August 2021 and remained around 1 until 30

June 2022 (Figure 4). This scenario further predicted no second COVID-19 wave, as the herd immunity threshold was reached during the first wave, and indicated limited NPI effectiveness and adherence since the start of the pandemic in NWS. As one health-worker reported:

> *'NPIs have little impact on the ground, and few people adhere to them. Despite the small number of interventions implemented, such as facemasks and hygiene practices, nothing seems to have significant impact except partial travel and border restrictions.'* (HCW2)

Scenario 2. Introducing variants

This transmission scenario predicted that introduction of a new variant in NWS would result in a second wave of infections, with hospital bed needs exceeding existing capacity unless NPIs are increased.

Scenario 2a. Extending NPIs for 12 months and introducing Delta variant with 20% vaccination coverage

This scenario predicted that introduction of the SARS-CoV-2 Delta variant in end of June 2021 would result in a second wave around December 2021, with 47,201 symptomatic and asymptomatic daily cases at its peak and 2,133 total deaths (i.e. a fourfold increase). It further estimated the numbers of hospital beds, ICU beds, and ventilators required at the peak of the second wave would be 543, 79, and 133 respectively. *Rt* was predicted to be above 1 between January and June 2022, reducing to 1 by June 2022 (Figure 5, Scenario 2a)

Scenario 2b. Ending NPIs and introducing Delta variant with 20% vaccination coverage

This transmission scenario, similarly to Scenario 2a, predicted introduction of the Delta variant would result in a second wave around September 2021, with 48,323 daily cases at its peak and 2,360 related deaths. It estimated the numbers of hospital beds, ICU beds, and ventilators required at the peak of the second wave would be 582, 79, and 133 respectively. *Rt* was predicted to be above 1 between January and June 2022, and reach 1 by June 2022 (Figure 5, Scenario 2b)

Scenario 2c. Increasing coverage of two NPIs with Delta variant and 60% vaccination coverage

This transmission scenario, which modelled increasing COVID-19 vaccination coverage to 60% and two NPIs (i.e. mask-wearing, handwashing) to 50% coverage, predicted a delayed second wave in November 2022, with 35,673 daily cases at its peak and 2,031 total death. It estimated that hospital occupancy would remain within a manageable threshold, with numbers of hospital beds, ICU beds, and ventilators required at the peak as 360, 79, and 132 respectively. Rt was predicted to hover just around 1 between January and June 2022 (Figure 5, Scenario 2c)

Scenario 3d. Extending NPIs for 12 months while introducing a more transmissible and lethal variant than Delta with 20% vaccination coverage (worst case scenario)

In this scenario, we increased variant parameters for transmissibility, lethality, and breakthrough infection probability to 2, 2, and 30 respectively. This scenario predicted that introducing a more transmissible variant with higher capacity to evade immunity and greater lethality by January 2022 would result in a third wave around March 2022, with lower peak than the second wave, with 17,946 symptomatic and asymptomatic cases daily at its peak and 3,484 total deaths (i.e. around a six-fold increase). It estimated that numbers of hospital beds, ICU beds, and ventilators required at the peak of the second wave would be 543, 79, and 133 respectively. *Rt* was predicted to increase over 1 between January and March 2022, then decrease to below 1 between March and June 2022.

DISCUSSION

Key findings

This is a first effort to model COVID-19 trajectories for NWS, a conflict-affected and opposition-controlled region of Syria characterised by fragmented health system governance and mass forced displacement, using a participatory tailored approach to selecting model parameters and scenarios. As such, it is both particularly challenging to model pandemic trajectories in this area and particularly necessary to document collaborative attempts to do so. Inclusion of semi-structured interviews additionally helped generate possible explanations for model findings related to under-reporting and potential herd immunity.

This study simulated multiple COVID-19 trajectory NWS scenarios:

- (1) predicting COVID-19 transmission when releasing four of the existing NPIs (i.e. handwashing, mask-wearing, safe-distancing, international travel ban) and no variant;
- (2a) predicting COVID-19 transmission with Delta variant, 20% vaccination coverage by June 2022, and continuation of low coverage of existing NPIs;
- (2b) predicting COVID-19 transmission with Delta variant, 20% vaccination coverage by June 2022, and ending existing NPIs ;
- (2c) predicting COVID-19 transmission with Delta variant, with an increased vaccination coverage to 60% by June 2022 combined with higher coverage of mask-wearing/handwashing;
- (2d) predicting COVID-19 transmission with a more lethal and transmissible variant than Delta as of January 2022, 20% vaccination coverage by June 2022, and extending existing NPIs.

These scenarios were chosen as most relevant by NWS policymakers. The no-variant scenarios, predicting around 47.5% population infection by June 2022 and no second wave, supports the theory that herd immunity was reached during the first wave in November 2020 in line with our interviewees assumptions that most of population was already infected or had cross immunity from similar SARS viruses such as the 2012 MERS epidemic in the region (CDC, 2021b). The Delta scenarios, predicting tripling of the death toll, exceed the ventilators threshold, and a second wave if the Delta variant emerges in NWS without increases in vaccination coverage, appears a likely concern without more rapid vaccine rollout given the rapid global spread of the Delta variant. In May 2021, COVAX began rolling out AstraZeneca vaccine in NWS, yet reports of delayed shipments, and concerns about cross-border negotiations that would further hinder vaccine implementation, are ongoing (World vision, 2021a, World vision, 2021b).

Scenario 2c indicated that increasing vaccination coverage to 60% by June 2022 coupled with an increased coverage of mask-wearing/handwashing would delay the second wave for two months, and reduce hospital occupancy to below the threshold of concern. These notable reductions could be because the NWS population is young, and 2% coverage targeting the most vulnerable, as required by COVAX, would already cover most elderly people.

Further research is needed into reasons for relative low case and death numbers (Statista, 2021, Our world in data, 2021). In the absence of serology data, it is difficult to explain underlying causes of the relatively low COVID-19 attributable death rates, compared with other low-income or conflict-affected settings, or validate estimates of the population infected (Our world in data, 2021). The relatively young population is likely one factor, as only 4% is over age 65. Another likely factor is under-reporting, as modelling predicted 47.5% of the NWS population would have been infected by May 2021 but only 1.2% were reported, and interviews also highlighted under-reporting. This study highlighted the need for serology data in NWS, to improve modelling estimation of numbers infected over time and track infections missed through lack of healthcare access or who were treated or died within community, which are likely higher than reported (CDC, 2021a). The literature supports potentially high under-reporting rates in a range of settings with weak reporting or fragmented infrastructure. For example, post-mortem surveillance in Ghana showed COVID-19 mortality under-reporting was higher in communities than health facilities (Mwananyanda et al., 2020), at 73% of total COVID-19 death. We triangulated model estimates with qualitative interview data to explore COVID-19 under-reporting and lower than expected transmission and case fatality rates. Health-worker theories were supported by an UDER community survey identifying fears of hospital infection or being isolated in community treatment centres, and preferring the care and support of their family when ill as barriers to seeking COVID-19 diagnosis and treatment (Relief Experts Association), 2020). Both health-workers and survey reinforced findings by Douedari *et al* that displaced families were more worried by daily challenges than COVID-19 and might not prioritise care-seeking (Douedari et al., 2020).

Overall, our modelling indicates that implementing NPIs other than vaccination in NWS is relatively ineffective and increasing their coverage would likely provide limited benefit in relation to the hardship caused unless there are radical changes in the virus. Current low-coverage NPIs appeared to mitigate local epidemic trajectory somewhat. Even introducing a new variant such as B.1.617, low population age provides some protection, which combined with vaccination of 60% of the population should be sufficient to decrease COVID-19 transmission in NWS and reduce deaths to 2,031. Therefore, responses should be balanced with negative impacts on the economy and psychosocial wellbeing of an already traumatised population (e.g. further school and religious facility closures could do more harm than good for child development/protection and social cohesion) (Roberton et al., 2020).

Limitations

Several limitations should be considered. First, model uncertainties include: (i) COVID-19 is a novel disease and knowledge on transmission dynamics is evolving, so model assumptions will also evolve; (ii) simulations will change with new data and interventions, e.g. widespread PCR testing, vaccination rollout, and potential treatments. Second, the CoMo model is age-structured and does not account for other transmission-relevant factors in NWS such as population density, displacement, poor housing, comorbidities, and COVID-19 protection measures in health facilities which may increase COVID-19 transmission. Third, unreliable morbidity and mortality data due to: (i) ongoing conflict; (ii) historically poor data management systems and inconsistent case identification in Syria; and (iii) predominantly manual health information systems across Syria. Fourth, fragmented COVID-19 response governance could affect NPI implementation and vaccine rollout.

Conclusions

This study used a contextualised CoMo model to support COVID-19 response decision-making in NWS. Modelling indicated that NPIs minimally affected COVID-19 transmission, with herd immunity potentially reached during the first wave in November 2020. Likely introduction of a new variant with only existing NPIs, would result in a second COVID-19 wave that would quadruple attributable deaths and exceed hospital capacity. Vaccination coverage of 20% is expected to reduce transmission while 60% vaccination coverage combined with 50% coverage of mask-wearing and handwashing is predicted to decrease hospital beds and ventilators occupancy to 227, and 130 respectively, which is below the existing threshold. However, introducing a new variant with higher transmissibility and immunity evasion capacity in January 2022 would result in a third wave around March 2022. Total COVID-19 attributable deaths are expected to remain relatively low, probably due to a young population. Thus, policymakers should increase vaccination coverage as quickly as possible rather than emphasising NPIs in this context, given potential negative socioeconomic consequences of NPIs for an already challenged population.

DECLARATIONS

Conflict of interest

All authors declare no conflict of interest.

Author contributions

MM conceived the study. MH and NA collected epidemiological data and HT and HR provided data for coverage parameters. MM, OAA, and WO conducted modelling with support from RA, BG, and HEC. OAA and YD collected and analysed qualitative data, with support from NH. MM and OAA drafted the manuscript with help from HEC, AA, and NH. NH critically revised for content. All authors contributed to interpretation and approved the version for submission.

Acknowledgments

Authors wish to acknowledge policymakers and health institutions in NWS, including the NWS Health Information System Unit, EWARN/ACU, UDER, and ARCS, for valuable insights and context for our findings. We thank the CoMo consortium for valuable technical support, in particular Professor Lisa White, Rima Shretta, and Dr Nathaniel Hupert. This study received technical support from the COVID-19 Research Response Fund, managed by the Medical Sciences Division, University of Oxford.

Funding

HEC's contributions were supported by NH's Foreign, Commonwealth & Development Office grant (40123957), while YD's and NH's contributions and open access fees were supported by NH's Medical Research Council/HSRI foundation grant (MR/S013121/1).

Ethics

The Saw Swee Hock School of Public Health Departmental Ethics Review Committee in Singapore (reference SSHSPH-052) and London School of Hygiene & Tropical Medicine Observational Research Ethics Committee in the UK (reference 17360) provided ethics approval.

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FIGURES AND TABLES

Table 1. Interviewee characteristics

ID	Professional Role	Sector	Gender
HCW1	Programme director	COVID-19 health centre	Male
HCW2	Internal medicine specialist	Hospital	Male
HCW3	Internal medicine specialist	COVID-19 health centre	Male
HCW4	Internal medicine specialist	Hospital	Male
HCW5	Internal medicine resident	COVID-19 health centre	Male
HCW6	Internal medicine specialist	Hospital	Male
HO1	Field manager	NGO	Male
HO2	Manager	NGO	Male
HO3	Private health worker	Private clinic	Male
HO4	Manager	Local health authority	Male
HO5	Orthopaedic resident	Hospital	Male
R1-O1	Manager	Local health authority	Male
R1-O3	Head of department	Hospital	Female
R2-O2	Trauma Specialist	Hospital	Male
R2-O3	Head of department	Hospital	Female
R2-O4	Team leader	NGO	Female
R3-O1	Manager	Local health authority	Male
R3-O2	Trauma Specialist	Hospital	Male
R3-O3	Head of department	Hospital	Female
R3-O4	Team leader	NGO	Female

Table 2. Summary of key modelling results

Parameter	Baseline	Scenario 1	Scenario 2A	Scenario 2B	Scenario 2C	Scenario 2D
Simulation period	01/06/2020-30/06/2022	01/06/2020-30/06/2022	01/06/2020-30/06/2022	01/06/2020-30/06/2022	01/06/2020-30/06/2022	01/06/2020-30/06/2022
Total COVID-19 cases at peak	NA	NA	1,051	1,084	567	1051
Reported and unreported cases at 2nd peak	NA	NA	47,201	48,323	35,673	47,201
Reported and unreported cases at 3rd peak	NA	NA	NA	NA	NA	
Peak date	NA	NA	Sep-21	Sep-21	Dec-21	Sep-21 (2nd Wave), March 2022 (3rd wave)
Total COVID-19 deaths	541	539	2,133	2,360	2,031	3,312
Minimum required hospital beds at peak	NA	NA	543	582	360	606
Minimum required	NA	NA	79	79	79	79

ICU beds at peak						
Minimum required ventilators at peak	NA	NA	133	133	132	133

NB: Baseline scenario (current situation) = extending low coverage NPIs for 12 months without any VOC and 2% vaccination coverage. Scenario 1 = Releasing low coverage NPIs without any VOC and 20% vaccination coverage. Scenario 2A = Extending low coverage NPIs for 12 months with Delta variant and 20% vaccination coverage. Scenario 2B = Releasing low coverage NPIs with Delta variant and 20% vaccination coverage. Scenario 2C = Increasing coverage of four NPIs with Delta variant and 60% vaccination coverage. Scenario 2D = Extending low coverage NPIs for 12 months with more transmissible variant than delta and 20% vaccination coverage.

Table 2: Coverage parameter for Non-pharmaceutical interventions

Parameters	**From**	**To**	**Scenario 1**	**Scenario 2A**	**Scenario 2B**	**Scenario 2C**	**Scenario 2d**
Handwashing	01/06/2020	31/12/2020	25	25	25	25	25
Handwashing	01/01/2021	30/06/2022	0	25	0	50	25
International Travel Ban	01/06/2020	30/11/2020	75	75	75	75	75
School Closures	01/06/2020	14/09/2020	80	80	80	80	80
Mask-wearing	01/06/2020	30/10/2020	15	15	15	15	15
Mask-wearing	01/11/2020	31/12/2020	15	15	15	15	15
Mask-wearing	01/01/2021	30/06/2022	0	15	0	50	15
School Closures	06/11/2020	12/11/2020	80	80	80	80	80
School Closures	01/06/2021	01/09/2021	80	80	80	80	80
International Travel Ban	01/12/2020	30/06/2022	0	30	0	30	30
Social Distancing	06/11/2020	31/12/2020	5	5	5	5	5
Social Distancing	01/01/2021	30/06/2022	0	5	0	5	5
Vaccination	01/05/2021	30/06/2022	20	20	20	60	20

Table 3. Variant related parameter for each modelled scenario.

Virus Parameters	**Duration**	**Transmissibility**	**Lethality**	**Breakthrough infection probability**	**Average duration of immunity**
Scenario 1	01/06/2020 - 30/06/2021	1	1	0	1.5 year
	01/07/2021 - 30/06/2022	1	1	0	1.5 year
Scenario 2b	01/06/2020 - 30/06/2021	1	1	0	1.5 year
	01/07/2021 - 30/06/2022	1.6	1	20	1.5 year
Scenario 2c	01/06/2020 - 30/06/2021	1	1	0	1.5 year
	01/07/2021 - 30/06/2022	1.6	1	20	1.5 year
Scenario 2d	01/06/2020 - 30/06/2021	1	1	0	1.5 year
	01/07/2021 - 31/12/2021	1.6	1	20	1.5 year
	01/01/2022 - 30/06/2022	2	2	30	1.5 year

Figure 1. Model corrections and fitting

Figure 1a. Uncorrected (left) and corrected (right) COVID-19 cases in NWS, March 2020-2021

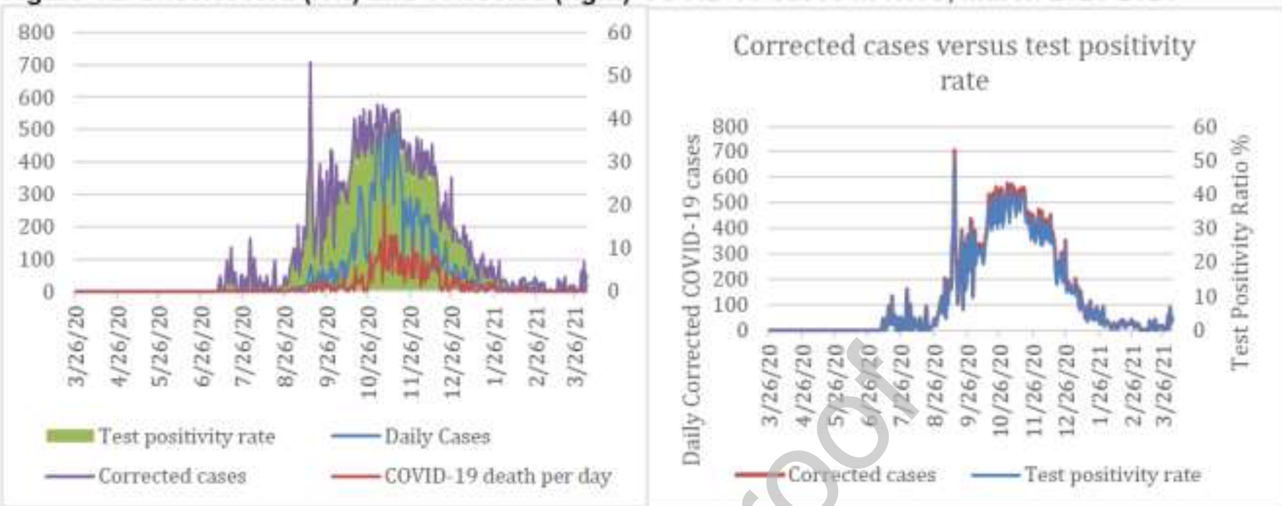
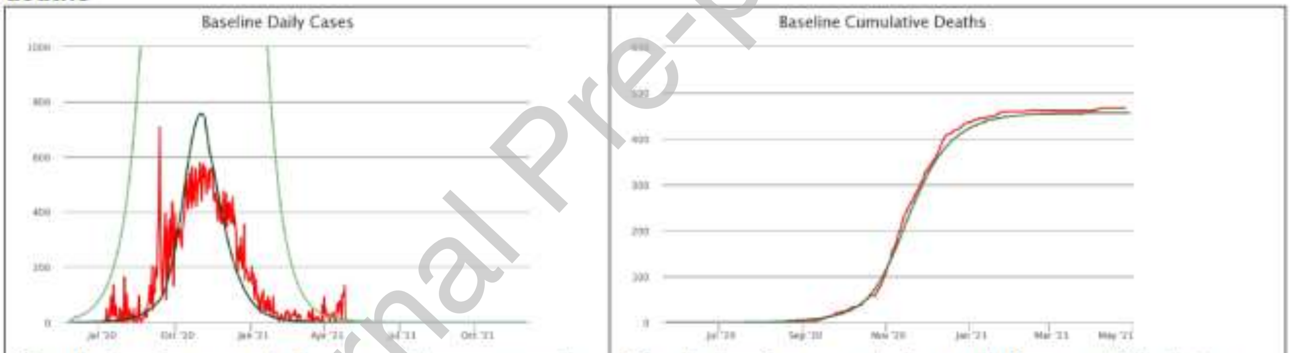


Figure 1b. Manual and automatic model fitting of daily reported cases and cumulative reported deaths



Graph showing reported cases data compared with model prediction.

Graph showing reported cumulative mortality data compared with model prediction.

NB: The red line represents data reported by ACU and the green line represents model predictions during the reporting period.

Figure 2. Timeline and coverage of non-pharmaceutical interventions in NWS

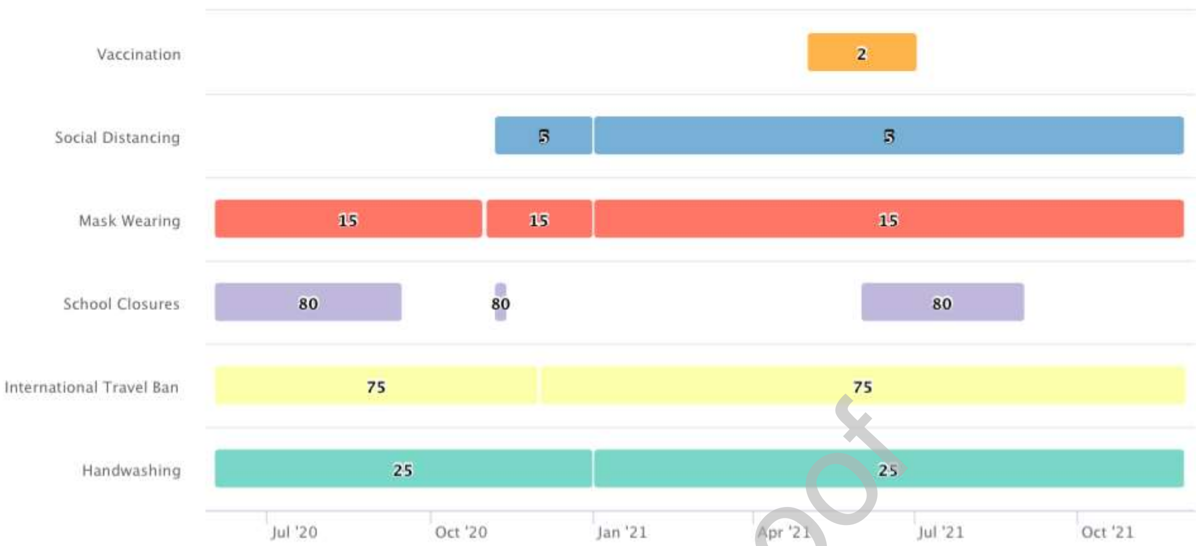


Figure 3. Baseline scenario

Figure 3a.Baseline effective reproductive number in NWS July 2020_ May 2021

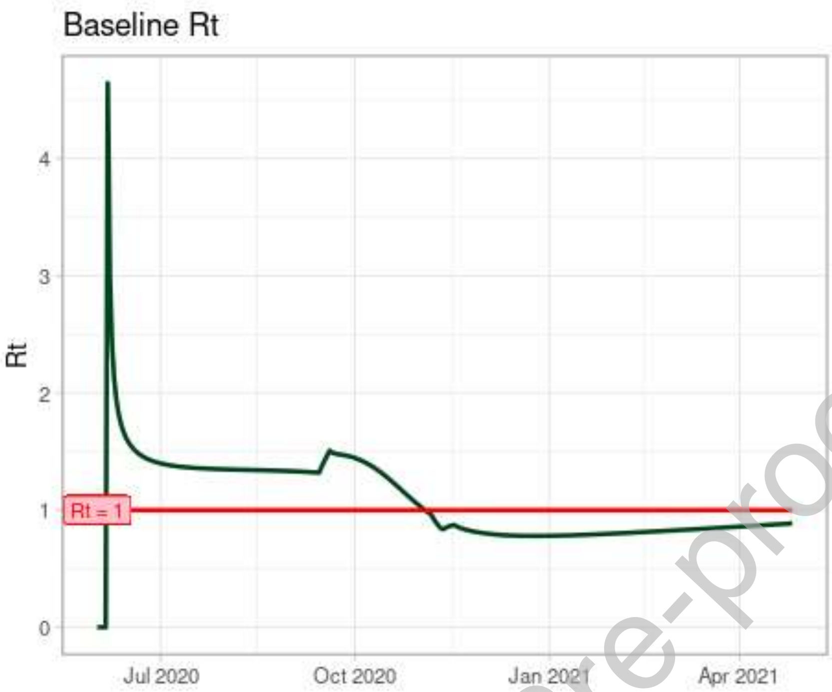


Figure 3b.Predicted and reported age-based hazard ratios (%) in NWS

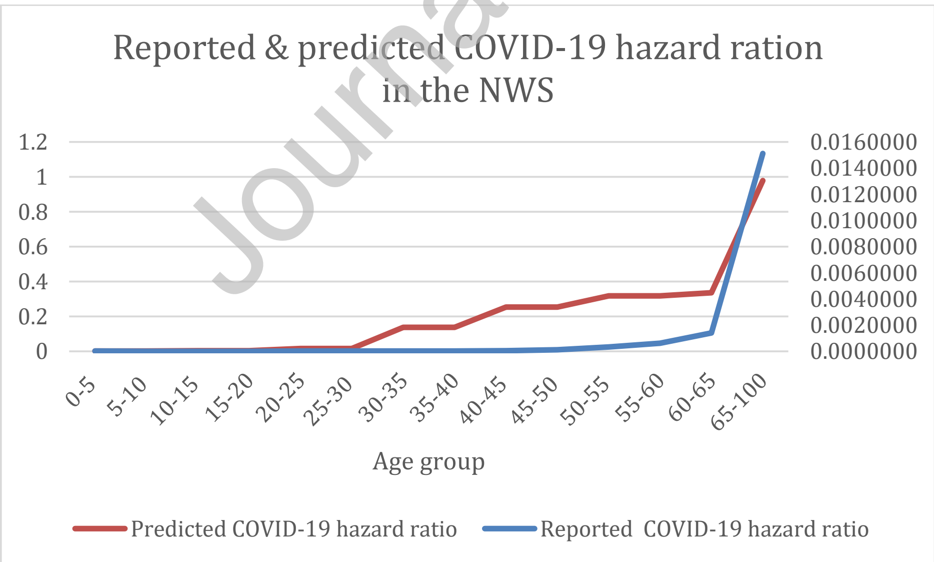
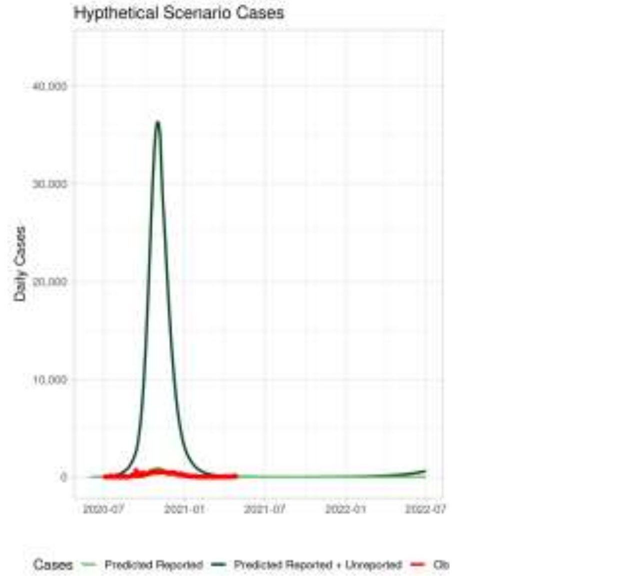
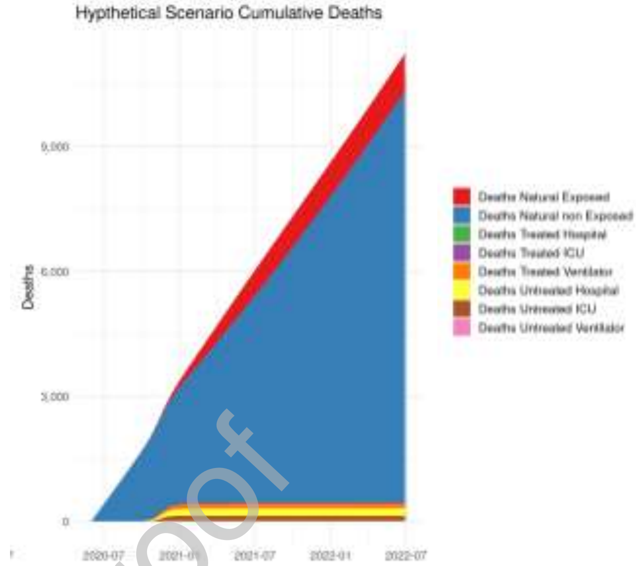


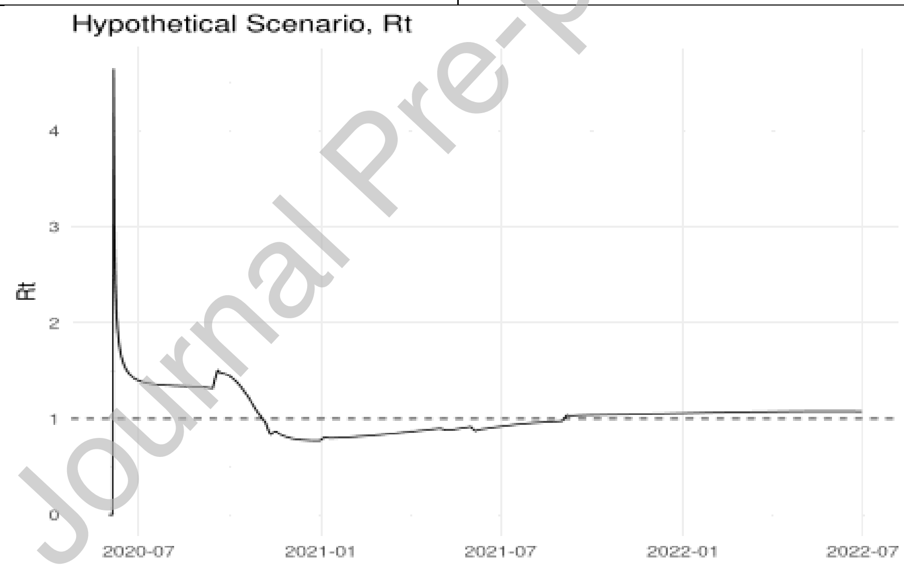
Figure 4. Scenario 1 Predictions of cases, deaths, and reproduction number



Scenario 1. Predicted reported and unreported cases over time

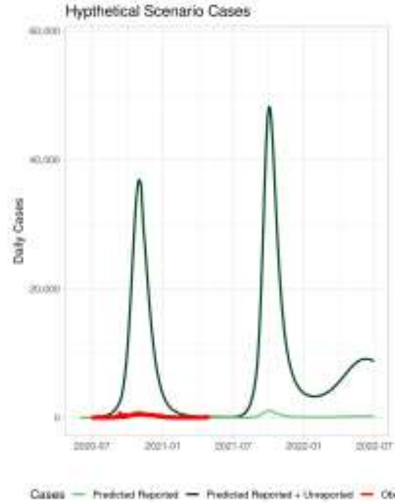


Scenario 1. Predicted cumulative deaths over time

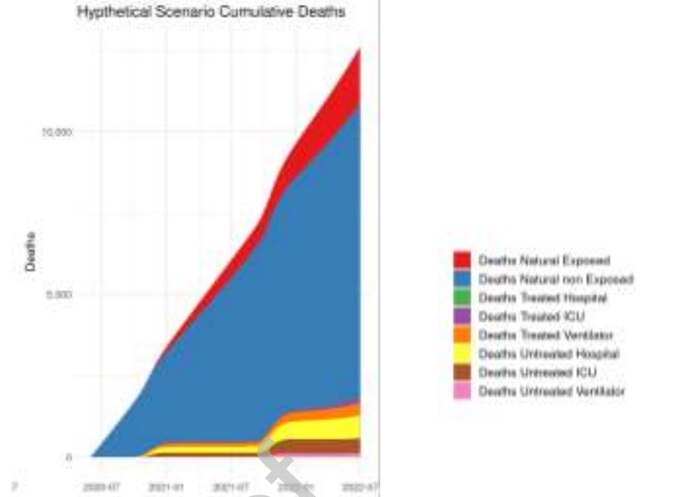


Scenario 1. Predicted reproduction number over time

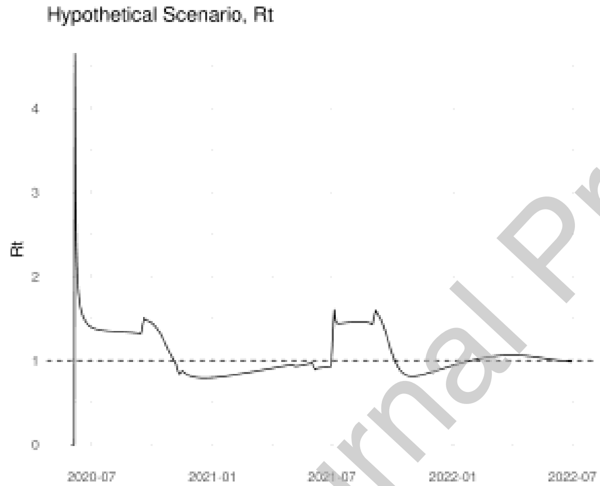
Figure 5. Scenario 2a-d predictions of death, cases, and R number with vaccination coverage of 20%, and 60%



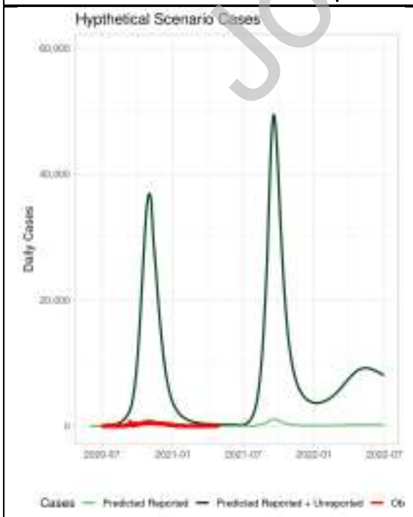
Scenario 2a. Predicted reported and unreported cases over time

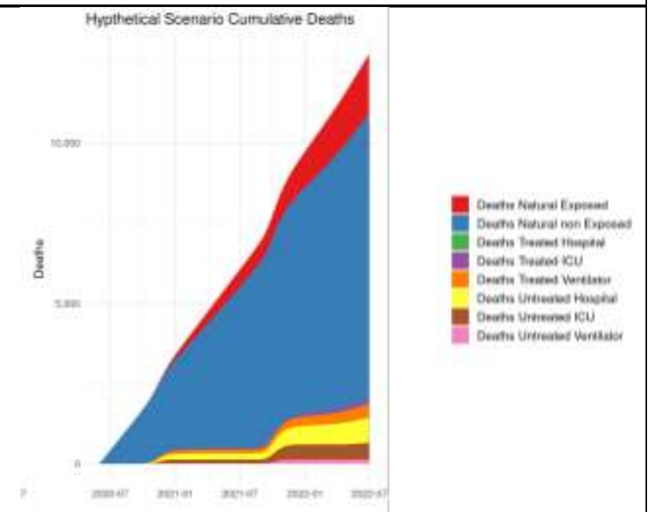


Scenario 2a. Predicted cumulative deaths over time

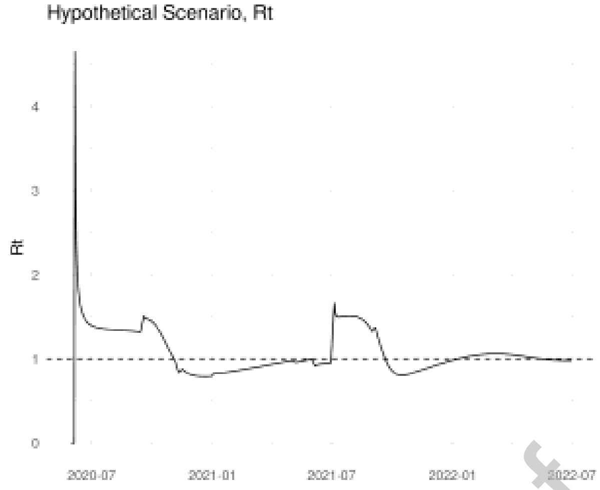


Scenario 2a. Predicted reproduction number over time

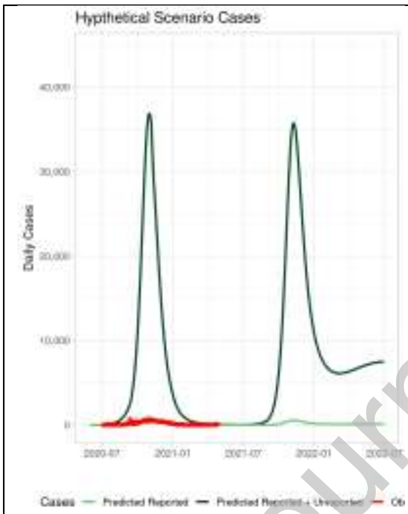
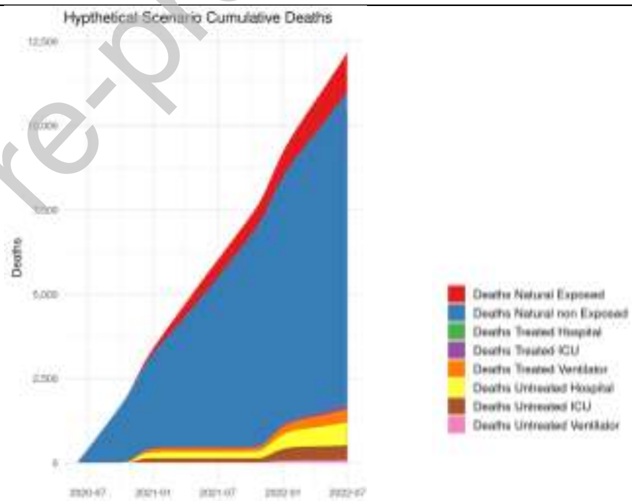


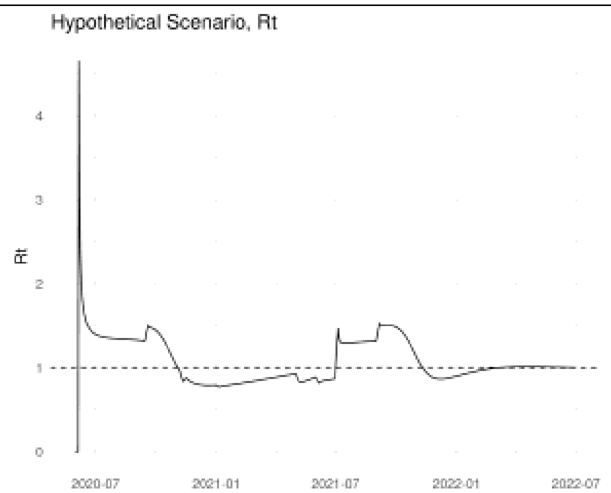


Scenario 2b. Predicted reported and unreported cases over time	Scenario 2b. Predicted cumulative deaths over time

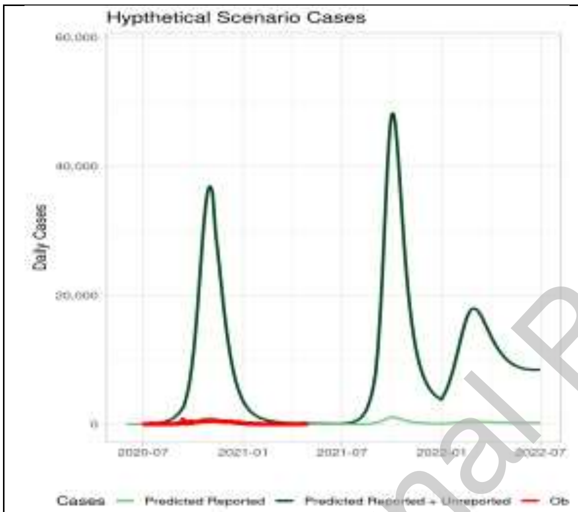


Scenario 2b. Predicted reproduction number over time

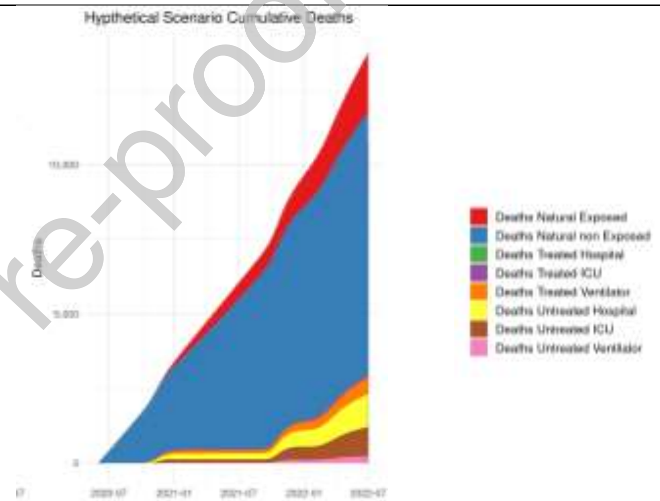
	
Scenario 2c. Predicted reported and unreported cases over time	Scenario 2c. Predicted cumulative deaths over time



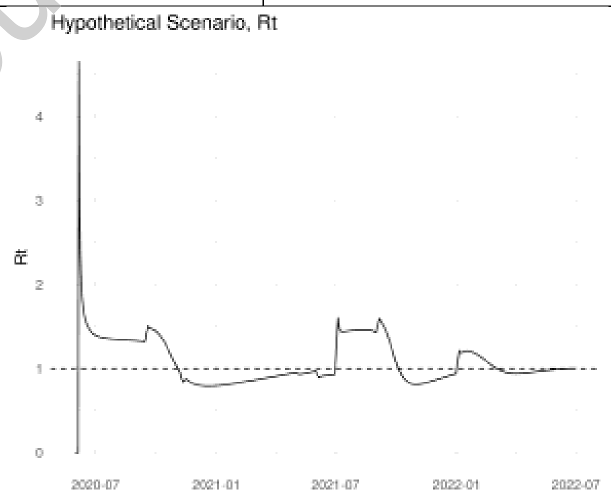
Scenario 2c. Predicted reproduction number over time



Scenario 2d. Predicted reported and unreported cases over time



Scenario 2d. Predicted cumulative deaths over time



Scenario 2d. Predicted reproduction number over time

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: