Could COVID-19 Mask and Vaccine Mandates Have Made a Difference if They Were Rolled Out Earlier?

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Abstract Hospitalisations and deaths due to COVID-19 in Canada declined after the first wave, thanks to nonpharmaceutical interventions and the vaccination campaign starting in December 2020, despite the emergence of highly contagious variants. We used an age-structured extended susceptible-exposed-infected-recovered compartment model to mimic the transmission of COVID-19 in Ontario from March 1, 2020, to May 31, 2021. We examined several counterfactual scenarios: (1) no mask mandates, (2) no vaccination, (3) instigating the mask mandate a month earlier and (4) rolling out the vaccine a month earlier. A 1-month-earlier vaccination program could have significantly decreased the number of cases and hospitalisations, but 1-month-earlier mask mandates would not have. It follows that the mandates that were implemented in practice were not optimal, but mostly performed well. Our model demonstrates that mask mandates played a vital role in saving lives in the first wave of the COVID-19 outbreak and that the vaccination programme was crucial to averting subsequent cases and hospitalisations after it was implemented.

Note: For citation purposes, please note that the question mark in "Smith?" is part of the author's name.

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1 Introduction

As of April 2024, COVID-19 had infected more than 700 million people and resulted in over 7 million deaths worldwide [1]. It is a respiratory disease with flu-like symptoms that is the causative agent of a disease that has significant public health concerns [2]. It was identified and gained traction in the city of Wuhan, in the Hubei Province of China at the end of 2019 [3], and was first identified in early December 2019 [4]. The most common symptoms at onset of COVID-19 illness are fever, cough and fatigue; other symptoms include sputum production, headache, haemoptysis, diarrhea, dyspnoea and lymphopenia [5–8]. The period from the onset of COVID-19 symptoms to death, depending on the age of the patient and their immune status, ranges from 6 to 41 days, with a median of 14 days [7]. Hospitalisations and deaths due to COVID-19 have declined since the first waves, thanks to masks, distancing and vaccinations. This has occurred even despite the emergence of highly contagious variants [9].

Age played a factor in the pattern of COVID infections, with distinct patterns for the young (0–19), working adults (20–60) and older individuals (60+). The time from symptom onset to hospitalisation was lower in the young (0.3–2.6 days) and older individuals (1–8.7), but much longer in adults of working age (3.6–9.8). Conversely, for individuals who recovered, the length of stay in ICU correlated with age, being low in the young (1.8–7.6), intermediate in working adults (3.2–13.1) and highest in older individuals (3.7–15.6) [10].

Examining the early days of COVID countermeasures can provide insights into public health policy decisions and also what might have been, in order to address the following questions. What did we get right? What could we have done better? These provide potential templates for managing future pandemics. We focus on Canada as an example. The province of Ontario reported the most cases, accounting for 34% of the country, as of August 26, 2022 [11]. See Fig. 1. We use data from the Ontario outbreak to fit a compartment model. Data is from StatsCan and Public

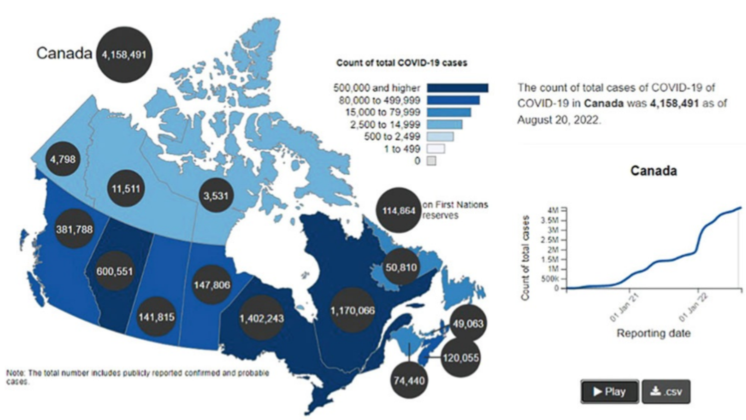

Fig. 1 Cases in Canada as of August 26, 2022. Image taken from [11]

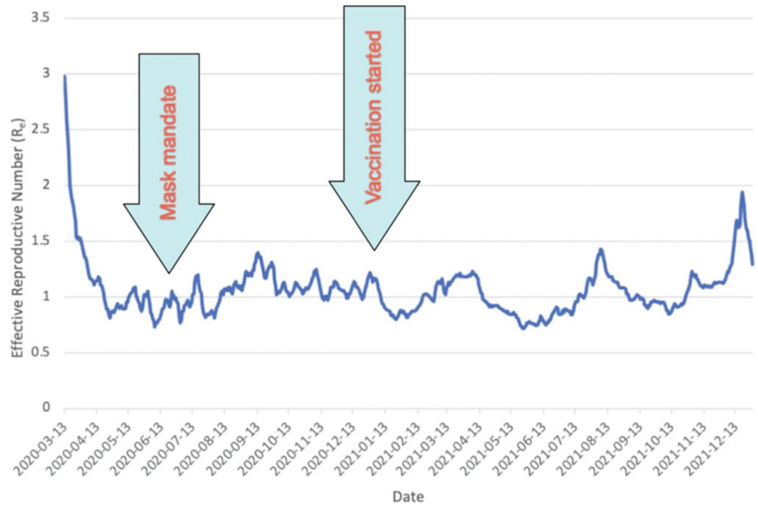

Fig. 2 The effective reproduction number in Ontario throughout the first 2 years of the pandemic, along with dates that the mask mandate was initiated and the vaccine rollout began

Health Ontario. Note that we did not have data on the number of asymptomatic individuals.

Two of the major control measures for escaping lockdown were the mask mandate and vaccination. The mask mandate was introduced in mid-June 2020. Vaccination began in Canada on December 14, 2020. See Fig. 2. Mathematical modelling during the pandemic played an important role in the public health response to COVID-19 in Canada [12, 13]. Models suggested that mask mandates were associated with a 22% reduction in weekly COVID-19 cases [14]. Canadians exhibited high levels of compliance with changing policies on mask usage, and trust in public health officials remained consistent during the early months of the pandemic [15]. Canada's COVID-19 vaccination strategy focused primarily on age, as well as medical and occupational risk factors, and was largely considered a success [16]. Early vaccine modelling suggested that prioritising essential workers over age-based rollouts would be more productive [17], while abandoning other protection options in favour of vaccination as the sole protective measure would be unwise [18].

Masks have several advantages and disadvantages. The biggest advantage is that they are an intervention method that can be applied immediately. However, mask efficacy has a wide variation, which ranges from 20 to 90% effective. Cotton masks lead to an approximately 20–40% reduction in virus transmission compared to no mask. The N95 mask has the highest protective efficacy: approximately 80–90% reduction in virus transmission. In contrast, cotton and surgical masks blocked more than 50% of the virus outward transmission, whereas the N95 masks showed approximately 90% protective efficacy [19]. They also require repeated application. Estimates show that mask mandates led to a 27% increase in self-reported mask wearing in public [14].

Vaccines have the disadvantage that there is a 14-day delay until protection. However, vaccination is a “one and done” event, requiring only a small number of doses, and the efficacy of all COVID vaccines was high: the efficacy from two doses of the AstraZeneca, Pfizer or Moderna vaccines ranged from 70 to 93% [20]. By mid-October 2021 in Ontario, 88% of the population 12 years of age and older had received at least one dose and 84% had received two doses [21].

We fit a compartment model to data from Ontario in order to answer the following counterfactuals: (1) How many cases and deaths were averted due to public health mitigation programmes? (2) What would have happened if the mask mandate had started a month earlier? (3) What would have happened if vaccination had been rolled out a month earlier?

2 The Model

In order to model a short period of the pandemic, we neglect natural birth, death and immigration. Hospitalised individuals are considered quarantined, and we only consider deaths from hospitalised cases. We only consider one COVID variant and apply a single dose of the vaccine, with no waning immunity.

We consider three age groups: young (0–19), working adults (20–59) and older individuals (60+). These three groups mimic the major age-related cohorts during the pandemic. Susceptibility (ϕ_i) varies by age group. The per-contact transmission probability $\beta(t)$ changes over time due to the implementation of interventions (e.g. mask mandates).We use a contact matrix c_{ij} to describe contacts between and within population subgroups. Exposed individuals become infectious after τ days. The proportion of symptomatic infections is a. Asymptomatic individuals will recover at a rate γ_A. Asymptomatic individuals have a lower infectiousness, characterised by ξ. A proportion of symptomatic infections (p_{hi}) will develop severe symptoms, at a rate θ_h, and then will be hospitalised; those who do not will recover at a rate γ_m. A proportion of hospitalised individuals (p_{di}) will die at a rate θ_d; those who do not will recover at a rate γ_h. Vaccination can reduce susceptibility to the disease, and the efficacy (r_i) is different among different age groups. Vaccinated individuals can become infected if the vaccine is not fully effective. See Fig. 3.

Susceptible individuals become infected at a rate $\beta(t)(1 - M)c_{ij}$ after encountering infectious individuals, where $\beta(t)$ is the probability of transmission per effective contact and c_{ij} $(i, j = 1, 2, 3)$ is the average number of daily contacts among subgroups. Both asymptomatic and symptomatic infections can transmit the infection; however, the asymptomatic individuals are assumed to have lower infectiousness, represented by ξ. After an incubation period τ, exposed individuals either become asymptomatic or symptomatic with proportion a. A proportion of individuals with symptomatic infection, p_{hi} will be hospitalised at a rate θ_h, with the remaining proportion recovering at a rate γ_m. A proportion of hospitalized individuals, p_{di}, die at a rate θ_d, with the remaining proportion recovering at a rate γ_h.

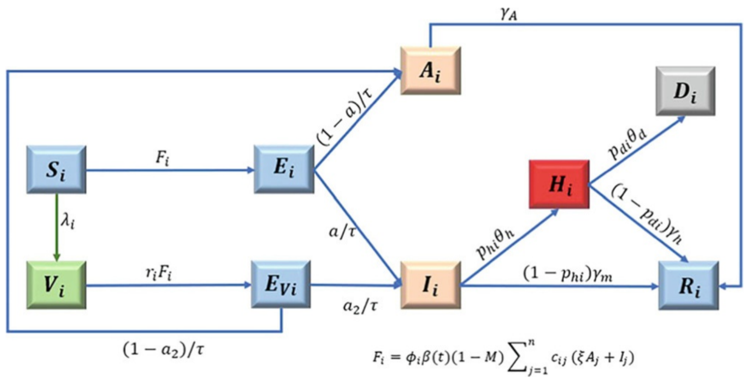

Fig. 3 The mathematical model

Vaccination will reduce the susceptibility of vaccinated individuals, and the efficacy of the vaccine $(1 - r_i)$ differs by age group. Vaccinated individuals may become infected and move to vaccinated-exposed compartments and thereafter become either symptomatic or asymptomatic. The vaccine reduces the proportion of symptomatic infection, so a_2 is lower than a, due to the vaccine-induced immune response. Due to the short timescale at the beginning of the COVID-19 pandemic, we only consider a single variant and no waning immunity of vaccination.

Our model is then

$$\begin{aligned}
S_i' &= -F_i S_i - \lambda_i \\
E_i' &= F_i S_i - 1/\tau E_i \\
E_{vi}' &= -1/\tau E_{vi} + r_i F_i V_i \\
V_i' &= \lambda_i - r_i F_i V_i \\
A_i' &= (1-a)/\tau E_i + (1-a_2)/\tau E_{vi} - \gamma_A A_i \\
I_i' &= \alpha/\tau E_i + a_2/\tau E_{vi} - (p_{hi}\theta_h - (1-p_{hi})\gamma_m) I_i \\
H_i' &= p_{hi}\theta_h I_i - p_{di}\theta_d H_i - (1-p_{di})\gamma_h H_i \\
D_i' &= p_{di}\theta_d H_i \\
R_i' &= \gamma_A A_i + (1-p_{di})\gamma_h H_i + (1-p_{hi})\gamma_m I_i,
\end{aligned} \tag{1}$$

where transmission is described by

$$F_i = \phi_i \beta (1-M) \sum_{j=1}^{n} \epsilon(t) c_{ij} (\xi A_j + I_j)/N_j.$$

Here, $\epsilon(t)$ describes the change in the contact rate due to public health control measures. This allows us to test counterfactual scenarios.

3 Results

In order to examine potential counterfactuals, we fit our model to data from Ontario and consider four scenarios:

1. With and without the mask mandate
2. With and without vaccination
3. Mask mandate initiated 1 month earlier
4. Vaccination rolled out 1 month earlier

3.1 Baseline Scenario

We begin by fitting the model to the Ontario data for the first three waves of the pandemic. Figure 4 shows the age-stratified fitting for symptomatic individuals, asymptomatic individuals, hospitalisations and deaths, with corresponding data plotted in dark blue. Note that we did not have data for asymptomatic individuals. However, given the excellent overall fits for the other three categories, we have faith that the model also describes the asymptomatic population well. The vertical light

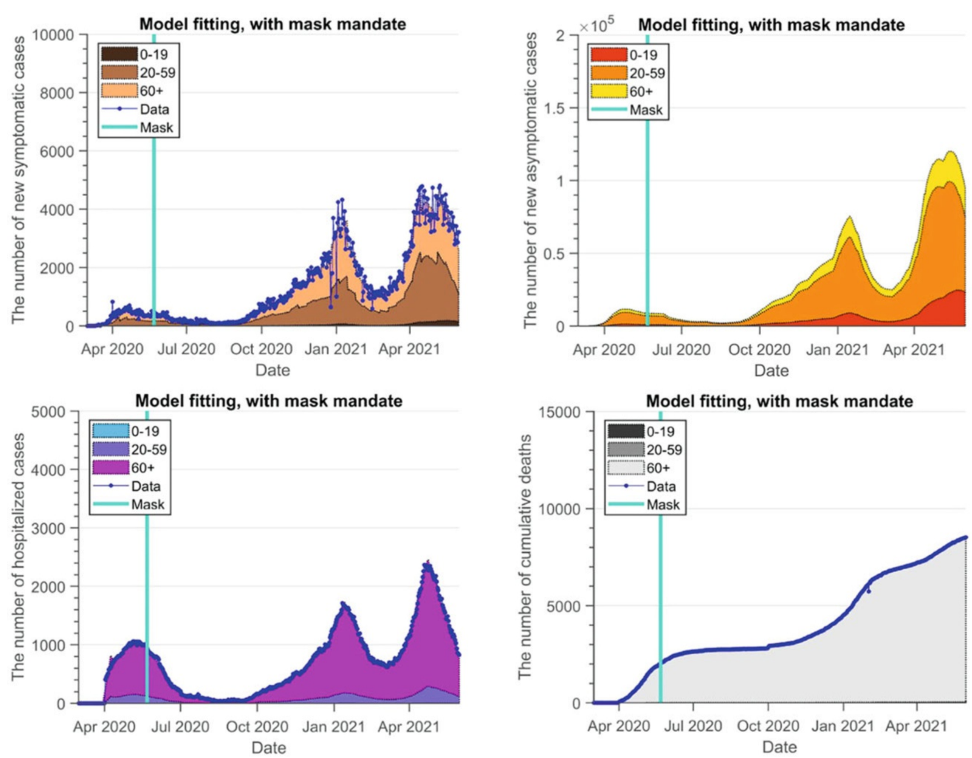

Fig. 4 Baseline scenario: The model matches the data (dark blue). Note that we do not have data for asymptomatics

blue line indicates when the mask mandate began. Note that the majority of cases are in working adults, whereas the bulk of hospitalisations and almost all deaths are among older adults.

3.2 *Counterfactual Scenario 1: What if Masks Hadn't Been Used?*

We looked at the effect of removing the mask mandate for symptomatic individuals, asymptomatic individuals, hospitalisations and deaths. We found that mask mandates reduced the overall cases by 35% and deaths by 69%, among which the largest number of cases, hospitalizations and deaths were averted in older individuals.

Figure 5 shows the model without the mask mandate and also plots the Ontario data in dark blue (see Fig. 4). Our model clearly shows that without the mask mandate, the peak of the second wave would have almost double the number of cases as the peak of the third wave did in reality. Note that the predicted third wave would have been much lower, as the pandemic would have essentially sped up.

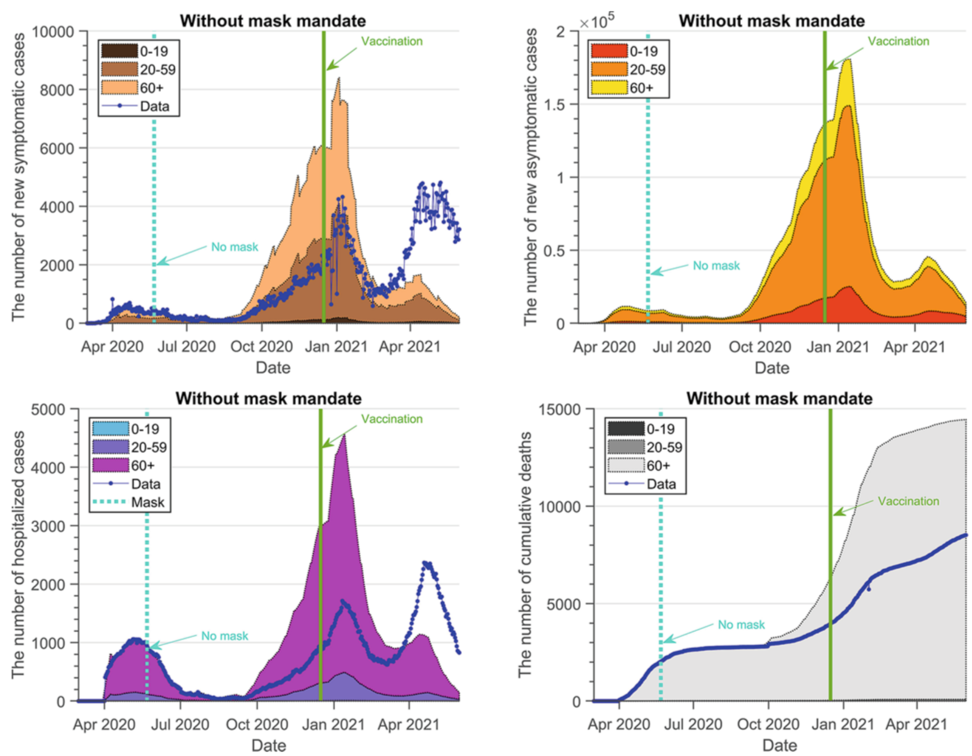

Fig. 5 Scenario 1: Without masks, the hospital system would have been overwhelmed in the second wave

In short, without the mask mandate, the early days of the pandemic would have fared much worse. The first wave would have been unchanged, but the second wave would have been disastrous. The hospital system would have been overwhelmed, and deaths in older individuals would have skyrocketed.

3.3 Counterfactual Scenario 2: What if There Had Neen No Vaccine?

Next, we looked at the effect of having no vaccine (but keeping the mask mandate). The vaccination programme contributed significantly to the mitigation of the third wave in Ontario, reducing symptomatic cases by 92%. Figure 6 shows the data as before, along with an indication of when vaccination started (green vertical line). In this case, the second wave would have proceeded as in reality, but the third wave would have seen a significant increase in cases and hospitalisations, more than doubling the peak of the third wave.

If the vaccine mandate had been dropped, the situation would have been worse eventually, in part because the vaccine started later. Without vaccination, the first and second waves would have been unchanged, but the third wave would have overwhelmed the health system, including for people under 60.

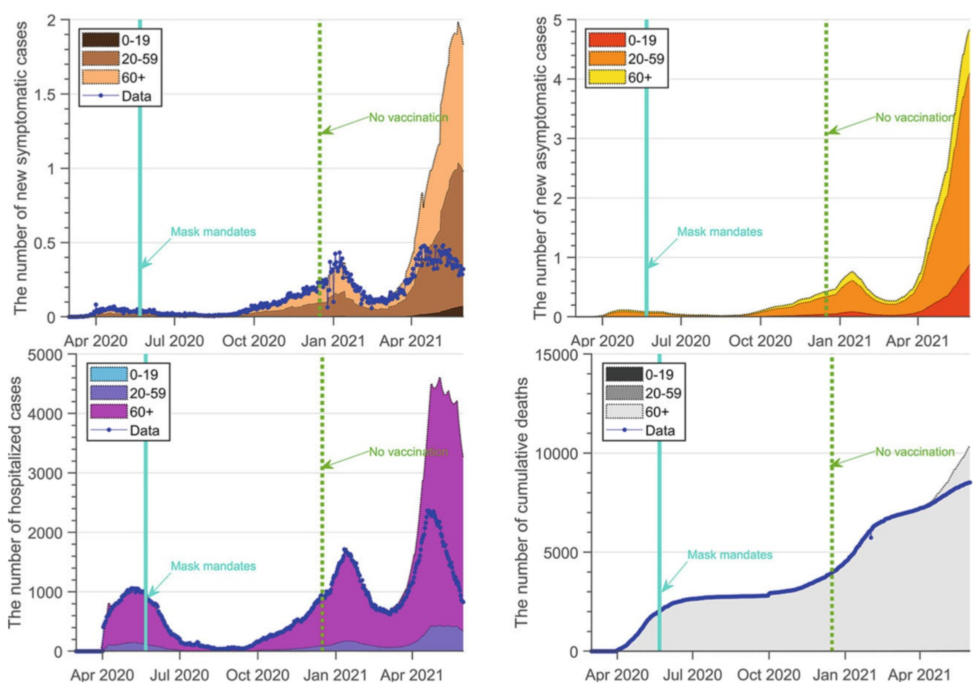

Fig. 6 Scenario 2: The absence of vaccination

3.4 Counterfactual Scenario 3: What if Masks Had Been Introduced a Month Earlier?

Given our confidence in the model, we now examine our first counterfactual possibility: introducing the mask mandate a month earlier. If the mandate had been enacted slightly earlier, would there have been a tangible effect on the outcome? Introducing the mask mandate a month earlier would have been possible, had governments and public health bureaus mobilised faster.

Examining past scenarios that did not occur in reality is something that mathematical modelling can easily do and which no other method can. This is where modelling can provide unique insights into "what-if" scenarios.

Figure 7 shows that introducing the mask mandate a month earlier would not have made a substantial difference. Deaths would have been slightly lowered, but the nature of the first three waves would have been almost identical to what we saw in reality. Specifically, the cumulative number of cases would have lowered by only 0.39%, and deaths would have lowered by 5.84%. The major benefits are a slight lowering of the hospitalisation rate in the second wave and a slight lowering of the death rate in the third wave.

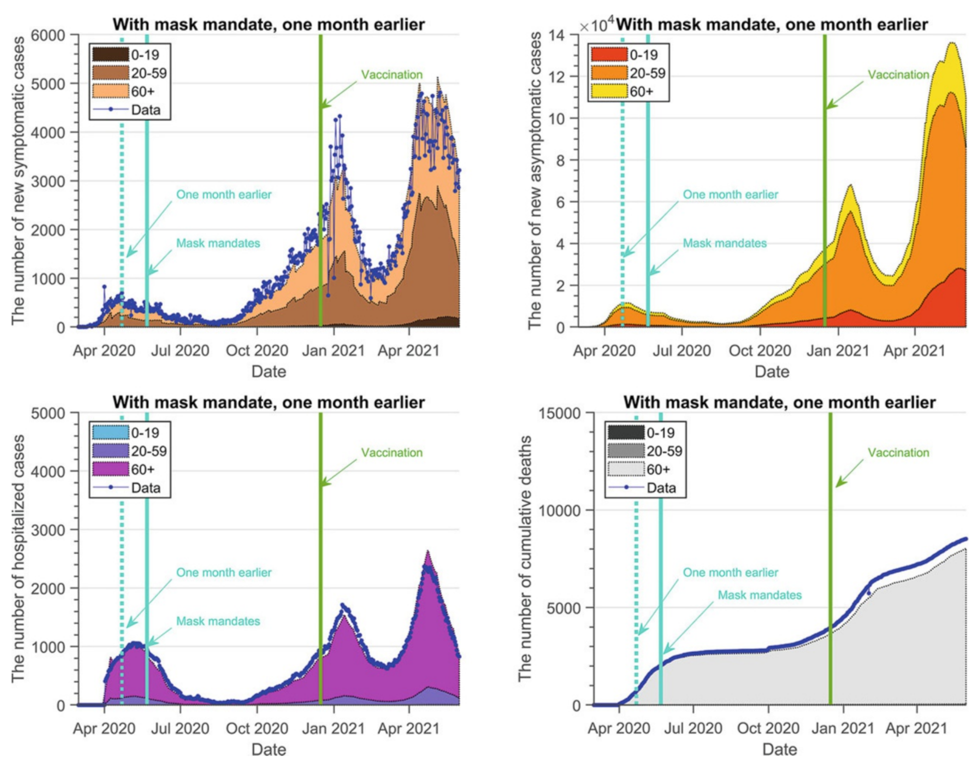

Fig. 7 Scenario 3: Introducing the mask mandate a month earlier

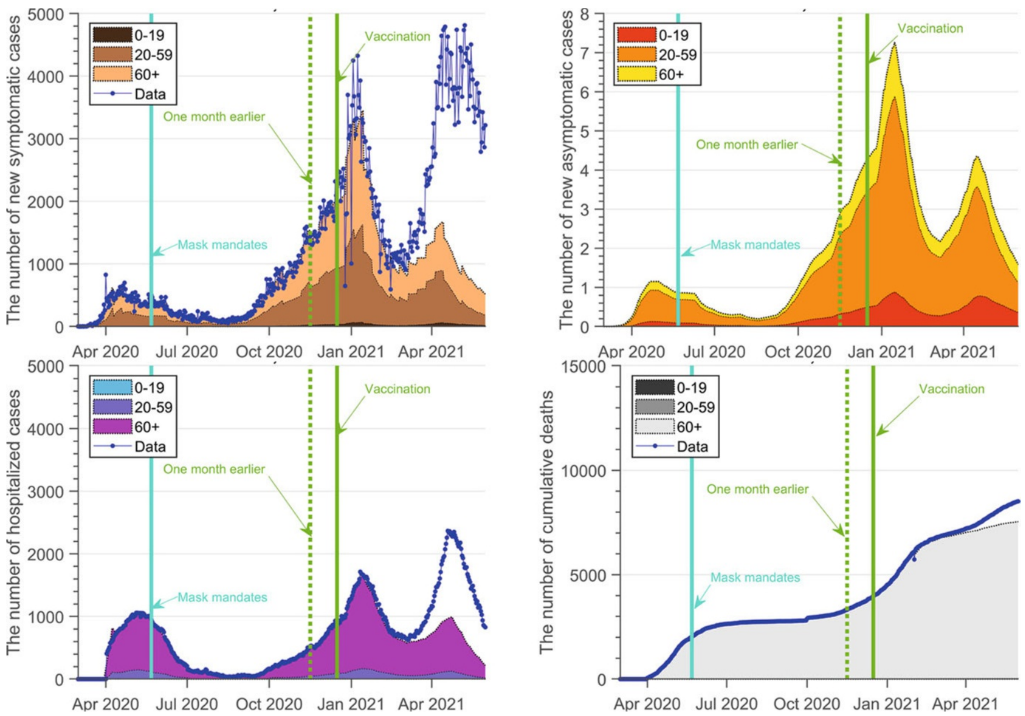

Fig. 8 Scenario 4: Rolling out vaccination a month earlier

3.5 *Counterfactual Scenario 4: What if the Vaccine Had Been Rolled Out a Month Earlier?*

We now examine our final counterfactual possibility: rolling out the vaccine a month earlier. This would have been harder to do than the mask mandate, but still potentially possible. Figure 8 shows the potential effect of instigating vaccination earlier than we did in reality.

Unlike the mask counterfactual, introducing a vaccine mandate a month early would have drastically changed the epidemic. Cases and hospitalisations in the third wave would have fallen significantly, with a 33% reduction in total cases and an 11% decrease in cumulative deaths.

We summarise the results of our four scenarios in Table 1 and Fig. 9.

4 Discussion

Mathematical modelling provides unique opportunities to examine "what-if" scenarios. Specifically, counterfactual scenarios like introducing masks and vaccines earlier than they were in reality allows us to examine the utility of measures that were enacted, as well as examine the possibility that such measures were never

Table 1 Summary of counterfactual analysis

As of May 31, 2021	Baseline model	Scenario 1 No mask mandate		Scenario 2 No vaccination		Scenario 3 Earlier mask mandate		Scenario 4 Earlier vaccination	
Cumulative symptomatic cases	589,051	797,549	35.40%	1,133,225	92.38%	587,434	−0.27%	393,517	−33.19%
Cumulative asymptomatic cases	13,951,038	18,955,377	35.87%	23,437,470	68.00%	13,896,088	−0.39%	9,228,437	−33.85%
Cumulative total cases	14,540,089	19,752,926	35.85%	24,570,695	68.99%	14,483,522	−0.39%	9,621,954	−33.82%
Cumulative deaths	8527	14,446	69.41%	10,366	21.57%	8029	−5.84%	7542	−11.55%

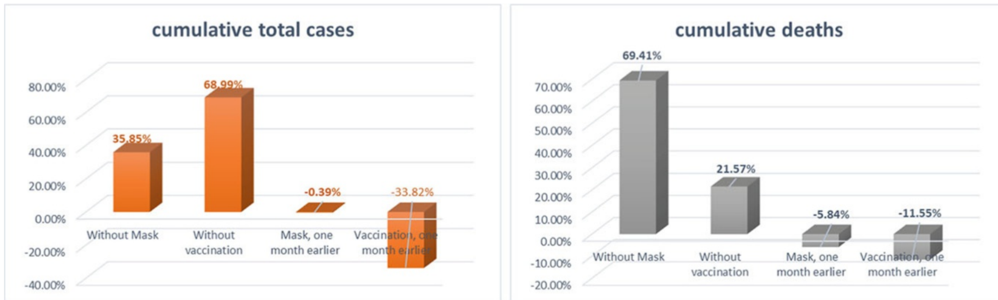

Fig. 9 Cumulative cases and deaths under our four scenarios

introduced. Our model fit the data extremely well, which suggests that tweaking the model to examine counterfactual scenarios produced reliable outcomes.

In particular, mask and vaccine mandates saved many lives, particularly among older individuals. The counterfactual scenario of introducing masks one month earlier would not have had a significant effect on the outcome. However, introducing the vaccine a month earlier would have drastically altered the course of the pandemic.

A major public health message during the early days of COVID-19 was that we needed to "flatten the curve" in order that the healthcare system not be overrun [22]. Our modelling clearly shows that removing either the mask mandate or vaccination would have caused a spike in hospitalisations (see Figs. 5 and 6). It is like that deaths would have increased even further in these cases, due to breakdowns in the healthcare system.

There are several limitations to our study, which should be acknowledged. Our model did not include vital dynamics such as births, deaths and immigration. Vaccination was described using a fixed rate, while deaths occurred only in hospitals, ignoring unrecorded deaths in the community. We limited our age structure to three classes.

Masks kept us safe in the early days of the pandemic, while vaccines are largely responsible for containing the COVID-19 epidemic. Both saved many lives during their implementation. By using modelling to examine the counterfactual scenarios, it is clear that the measures we did enact were not optimal but mostly performed well.

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