Impact of Public Health Interventions on the Spread of COVID-19 in Ontario

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Appendix

References

Introduction

The World Health Organization declared the novel coronavirus disease 2019 (COVID-19) as a global pandemic in March 2020[1], and Canada was not spared in the spread of the disease. Since the first reported case on January 25, 2020[2], the number of cases has increased to over 1.3 million[3], more than half a million of which were reported in Ontario as of May 20th, 2021[4].

The province of Ontario has implemented a number of public health interventions such as province-wide lockdowns, a mandatory mask policy and vaccinations to curb the spread of the disease[5]. But what would happen to the cases and deaths if these measures were lessened, or not in place at all?

In this case study, we seek to answer this question by exploring different scenarios of public health interventions in Ontario using a modified SEIR compartmental model. Compartmental models are mathematical models used to simulate the spread of infectious diseases within a population as well as to project trends given a series of parameters and assumptions[6].

Objectives

1. What would have been the impact of not having the winter 2020 or the spring 2021 province-wide lockdown on the total number of prevalent cases, hospitalizations and deaths of COVID-19 in Ontario?

2. For different rates of vaccination, how long will it take Ontario to reach the target fully vaccinated population for reopening, as well as the herd immunity threshold? For herd immunity, how would the peak number of prevalent cases and deaths be affected for each vaccination rate?

Methods

Model Overview

To simulate the COVID-19 epidemic in Ontario, we build upon the Susceptible-Exposed-Infected-Recovered (SEIR) compartmental model by adding the states of Hospitalized (H), Fatal (F) and Vaccinated (V). All calculations are shown in the appendix.

$$N = S + E + I + R + V + H + F$$

$$\frac{dS}{dt} = -\beta\frac{S(t)I(t)}{N} + iR(t) - ve_vS(t)$$

$$\frac{dE}{dt} = \frac{\beta S(t)I(t)}{N} - lE(t)$$

$$\frac{dI}{dt} = lE(t) - (r_o + +d_l)I(t)$$

$$\frac{dH}{dt} = p_h r_o I(t) - (r_h + d_h)H(t)$$

$$\frac{dR}{dt} = (1 - p_h)r_o I(t) + r_h H(t) - iR(t)$$

$$\frac{dF}{dt} = d_l I(t) + d_h H(t)$$

$$\frac{dV}{dt} = ve_vS(t)$$

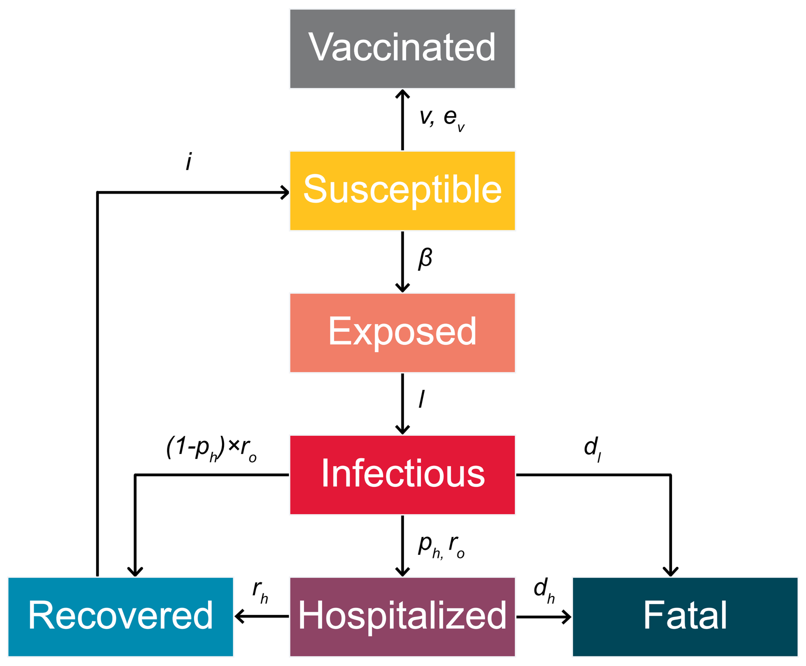

Figure 1. State diagram

Model Assumptions

- The population size, N, remains constant over time. We do not take into account birth rates and natural death rates.
- The Vaccinated state includes only fully vaccinated individuals.

Table 1. Model Parameters

Parameter	Description	Values: Winter 2020 Lockdown	Values: Spring 2021 Lockdown	Values: Future Vaccinations	Assumptions	Source
i_l	1/temporary immunity (per day)	1/140				Gudbjartsson et al., 2020; Hall et al., 2021[7]
l	1/incubation period (per day)	1/5.5				Public Health Ontario[8]
p_h	Proportion of COVID-19 cases which are hospitalized	0.074				Government of Canada[9]
r_h	Recovery rate of hospitalized individuals (per day)	1/15				Canadian Institute for Health Information[10]
r_o	Recovery rate of infectious individuals (per day)	1/14			We assume this is also the same as the rate of infectious individuals moving to the hospitalized state.	Ontario Data Catalogue[11]
β	Transmission rate (per day)	1.07/4.5	1.14/4.5	0.836/4.5	Calculated by $\frac{\text{Effective reproduction number}}{\text{Serial Interval}}$	Ontario Data Catalogue[12]; Public Health Ontario[13]
d_l	Death rate of infectious individuals (per day)	2.91e-03	2.36e-04	8.38e-05	We assume this is the same as the death rate from LTC homes	Ontario Data Catalogue[11]
d_h	Death rate of hospitalized individuals (per day)	0.015	0.0156	0.0147	We assume that all deaths that do not occur in LTC, occur in hospitals	
e_v	Vaccine effectiveness	0.942		1*	We assume the vaccine effectiveness is the same as vaccine efficacy.We take a weighted average of the vaccines currently in use in Canada.	Pfizer[14]; Moderna[15]; Astrazeneca[16]; COVID-19 Tracker Canada[17]; Government of Canada[18]
v	Vaccination rate (per day)	0 [first 12 days] 1.30e-04 [otherwise]	2.44e-04	3.47e-04 [average over Jan-May 2021] 1.31e-03 [average over May 15-29] 2.68e-03 [rate on May 29]	Only Susceptible individuals move to the Vaccinated state.	Ontario Data Catalogue [11], [19]

*We assume the vaccine effectiveness is 1 for easier comparison with the Ontario reopening plan and so that people who took two doses of vaccine don't have to retake it again.

Public Health Interventions

- The model was run in the period of the winter 2020 province-wide lockdown (December 26, 2020 - January 25, 2021) and the spring 2021 province-wide lockdown (April 03, 2021 - present at the time of writing (May 29, 2021)).
- Additionally, we use our model to predict when we will reach 20% and 25% of the population vaccinated with 2 doses (Steps 2 and 3 of the Ontario reopening plan[20]) and herd immunity (60% of the population fully vaccinated). We also assume that no other public health interventions are introduced in our analysis.
- We calculated the proportion of the population required to be vaccinated for herd immunity using the basic reproduction number, R_0 = 2.3[21], as follows: $(1 - \frac{1}{R_0}) \div \text{vaccine effectiveness} = \frac{1/2.3}{0.942} = 60.00\%$

Results

For both lockdowns, the data shows a decrease in prevalent and hospitalized cases and a slowing down of deaths per day. However, without a lockdown, our model predicts a continuously increasing trend where the number of prevalent, hospitalized, and fatal cases would be substantially higher.

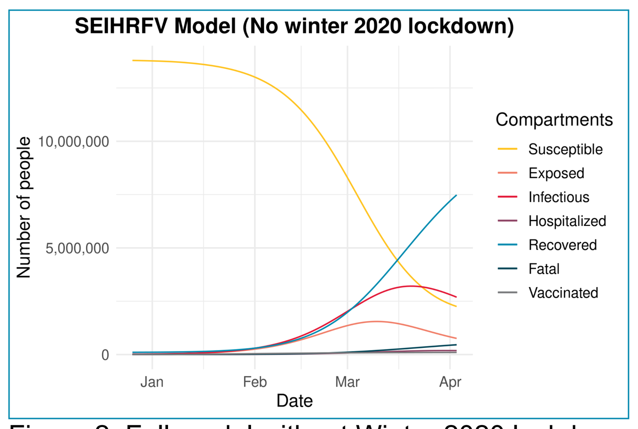

Figure 2. Full model without Winter 2020 lockdown

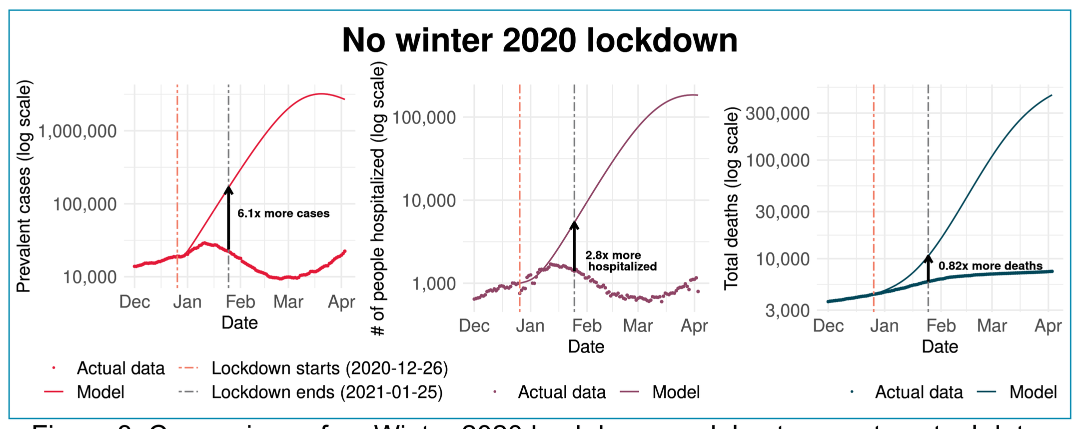

Figure 3. Comparison of no Winter 2020 Lockdown model outcomes to actual data

Without the second lockdown, the number of hospitalizations would exceed 55,000, which is more than the number of hospital beds available in Ontario[22].

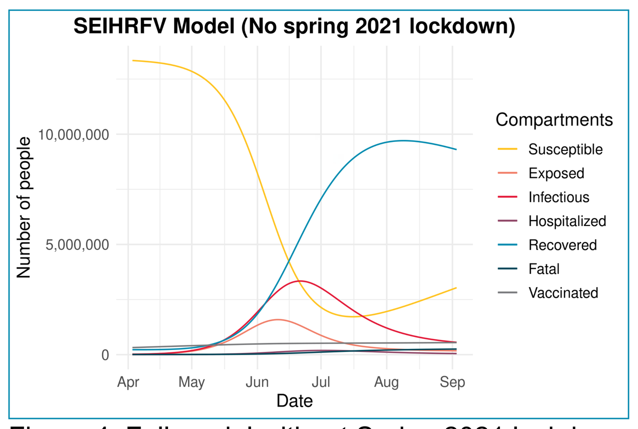

Figure 4. Full model without Spring 2021 lockdown

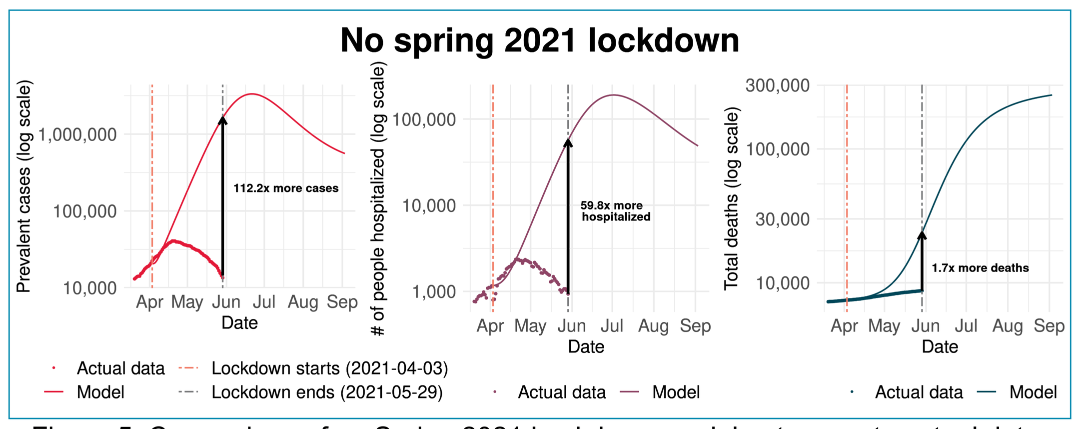

Figure 5. Comparison of no Spring 2021 Lockdown model outcomes to actual data

The slowest vaccination rate indicates that it will take 10 years to reach herd immunity, while the fastest vaccination rate predicts that herd immunity will be within reach before the end of 2022.

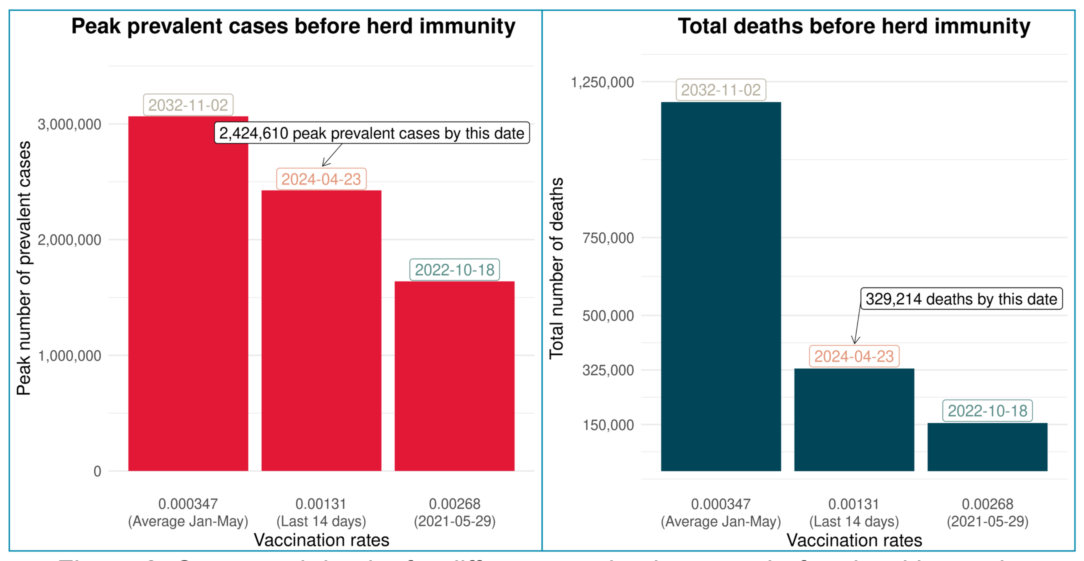

Figure 6. Cases and deaths for different vaccination rates before herd immunity

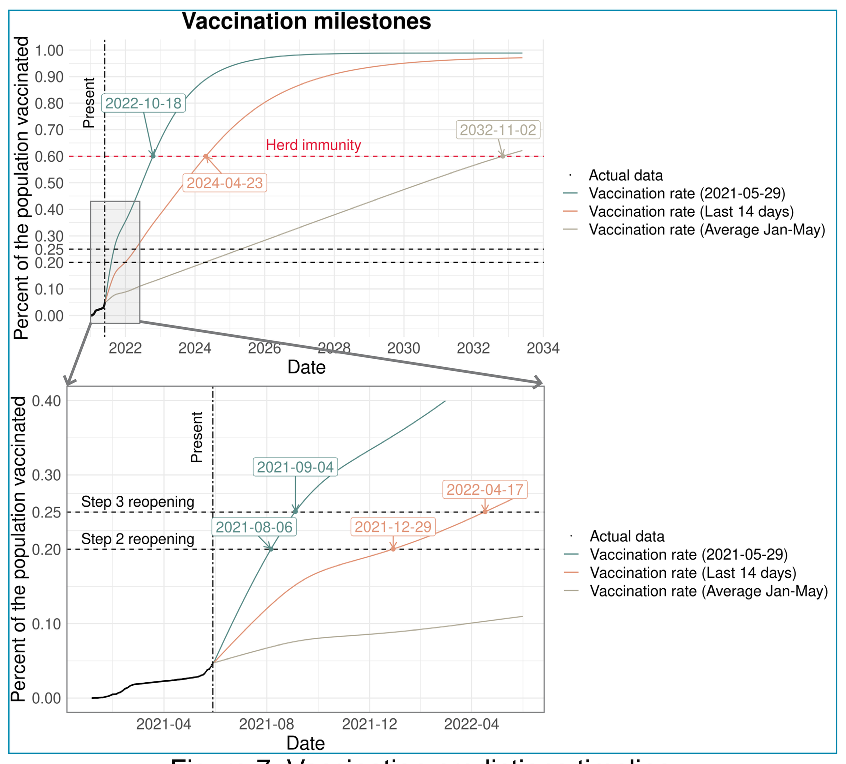

Figure 7. Vaccination predictions timeline

Conclusions

Not having the province-wide lockdowns in Ontario would have led to considerably more cases, hospitalized individuals and deaths. In addition, we conclude that higher vaccination rates would lower the number of cases and deaths. Keeping the current rate of vaccination or faster would comply with the reopening timeline proposed by the Ontario government, and achieve herd immunity before the end of 2022.

Strengths

1. The additional compartments of Hospitalized (H), Fatal (F) and Vaccinated (V) give a more complex and realistic simulation of the situation in Ontario.
2. We built our model upon referring to multiple previous research and expanded on them by taking vaccinations into account.
3. Our model takes into account the situation of COVID-19 reinfection by including waning immunity.
4. Our study extended on previous research by predicting the time it will take for Ontario to reach herd immunity.

Limitations

1. Our deterministic model assumes constant values for our parameters and does not take into account real-world variability such as in the occurrence of 'superspreader' events where the reproduction number will change. A stochastic model would better handle these uncertainties by providing a range of possible outcomes.
2. We did not evaluate the impact of other public health interventions such as wearing a mask and social distancing since with a combination of them already being in place in the province, it was difficult to isolate their effects from the data and estimate the contact rates.
3. There may be a delay in the documentation of cases and some cases may go unreported so our estimated values might not be entirely accurate.
4. Our model does not take into consideration the different parameter values for each age group. For instance, different age groups have varying contact rates – someone who goes to school vs. someone in a long-term care home are affected differently. In the future, we can take these into account by using age-specific SEIR modelling.
5. Our model does not account for the delays between the first and second doses of vaccination in our vaccination rate nor partially vaccinated individuals. We assumed a constant rate of full vaccination, but in reality, we would expect an increase in the rate of vaccinations as more vaccines become available, and when more people get the first dose.
6. In our prediction for herd immunity, we do not account for the variants of COVID-19 (VOCs), and the actual vaccine effectiveness may not equal the vaccine efficacy. Without the VOCs, the herd immunity threshold will be higher.

Key Takeaways

1. Without the lockdowns, the number of prevalent cases, hospitalizations and deaths in Ontario would be much higher.
2. The higher the vaccination rate, the fewer deaths and the peak number of cases there would be.
3. Keeping up the current rate of vaccination of fully vaccinated individuals would comply with the reopening timeline proposed by the Ontario government, who aims to enter steps 2 and 3 of reopening within the next few months.
4. Herd immunity can be reached by the end of 2022 if the current rate of vaccination of the second dose is maintained.