COVID-19: PHAC Modelling Group Report

Public Health Agency of Canada | Agence de la santé publique du Canada

MARCH 24, 2022

1 EXECUTIVE SUMMARY AND CONTEXT

This is the March 24, 2022 overview of modelling studies conducted and collated by the PHAC Modelling Group. Summaries below are hyperlinked to the related section of the report for full details.

CURRENT SITUATIONAL AWARENESS

Domestic

The effective reproduction number (Rt) for Canada as of March 12, 2022, was 0.9. On that date, *Rt* was below one in all major provinces. A decline in *Rt* in late December and early January was likely due, in part, to changes in testing practices. However, a similar signal from wastewater analysis suggests that the decline was at least partly due to a genuine decline in transmission as well. Recently, *Rt* values in Saskatchewan have begun to rise, suggesting a potential resurgence of cases in that province.

The short-range statistical forecast for Canada up to March 31, 2022 is:

- 37,492 cumulative deaths (range 37,347 to 37,601).

Short-range forecasts for cases were not produced given the changes to testing protocols across Canada. The incidence of new deaths is projected to remain steady throughout the next week in Canada.

The long-range dynamic modelling forecast (PHAC-McMaster University model) suggests that, nationally, infections, hospital occupancy and hospital admissions will continue to decline, but will likely resurge with the lifting of restrictions. However, the number of COVID-related hospital admissions and occupancy rates are forecast to be lower than those seen in January 2022 for all provinces, with the possible exception of Alberta. Due to changes in data availability, there is significant uncertainty in these forecasts.

The Wastewater-based forecasts and effective reproduction number estimates suggest a decreasing trend of infections and data suggest that under-reporting of cases continue to occur. Case surveillance suggests potential resurgence in some locations, but these are not yet confirmed by the wastewater data, which lags about one week behind case data due to processing delays.

International

Importation risk modelling for the week of March 13 to 19, 2022 suggests that an estimated 4,218 people with COVID-19 came to Canada including 2,944 air travellers, primarily from Mexico, the United States of America (USA), and Germany, and 1,274 land travellers from the USA. From March 13 to 19, 2022, the estimated percentages of imported cases from air travel that may be variants of concern or variants of interest are 79.17% B.1.1.529 (Omicron), 19.82% BA.2 (Omicron) and 0.03% B.1.617.2 (Delta). Many jurisdictions are limiting the use of COVID-19 tests, impacting global case count, testing data estimates and the proportion of people who have been previously infected with Omicron.

Assessment of the impact of interventions on the COVID-19 epidemic in Canada and other countries using the Oxford University stringency index:

- In Canada, the stringency index increased to 78 in response to the Omicron wave in late December 2021, then, after cases declined, recently decreased to 69.
- Internationally, disease activity greatly varies across many countries: many countries have eased public health measures based on current COVID-19 trends, health care capacity, and vaccine coverage, while some have maintained or re-implemented measures.

DYNAMIC MODELLING

The Agent-based model explored the impact of increasing acceptance of boosters, and deploying them at an expedited rate, on Omicron infections and hospitalisations in the coming months. Results suggest that, despite relatively low booster uptake, the current lifting of public health measures may not cause a resurgence of cases that would exceed the number of hospitalisations and deaths observed in previous waves. Overall, comparing different scenarios for booster uptake, as well as speed and timing of booster rollout, there were only small differences in cases, hospitalisations and deaths. Results suggest that delaying increased uptake of boosters until early fall had the greatest impact on reducing a wave in fall-winter 2022-2023.

The SEIR compartment model was used to explore the effect of boosters on the Omicron wave. Additionally, following the most recent Omicron wave, scenarios with different speeds and degrees of waning immunity along with different levels of booster administration were examined to see their effect on subsequent waves of COVID-19. Results suggested that booster administration in 2021 may have significantly reduced the Omicron wave of hospitalisations. However, scenarios in which there was rapid administration of additional boosters, to reach 90% of the eligible population, resulted in only a small reduction in hospitalisations during spring 2022. In scenarios where booster administration is rapidly deployed following the Omicron wave, the results associated with a simulated fall 2022 resurgence did not show a significant reduction in hospitalisations. These findings support studying the timing of booster administration to determine optimal efficacy.

CONTEXT

The COVID-19 pandemic has spawned extensive international research to inform both clinical and public health evidence-based actions to mitigate its effects. The objective of this publication is to share the results of the COVID-19 PHAC Modelling Group on domestic situational awareness, international situational awareness, dynamic modelling studies looking at the COVID-19 epidemic and public health measures, and any Special Reports that may arise from the Modelling Group or external partners. The Annexes identify the list of contributors, and more in-depth information on the methodologies of the studies.

It is important to note the limitations of modelling studies. They rely on estimates that may be derived from other countries and therefore there is inherent uncertainty when extrapolating this to Canada. Furthermore, the data from Canada and globally are constantly evolving, as a result, there may be a lag time before estimates in the model and its outputs are able to reflect this.

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2 DOMESTIC SITUATIONAL AWARENESS

2.1 EFFECTIVE REPRODUCTION NUMBER FOR CANADA

Key points

- On March 12, 2022, the national *Rt* was 0.9; and provincial *Rt* was below 1 for all major provinces except Saskatchewan where the *Rt* hovers around 1.
- Decline in *Rt* in late December and early January was likely due, in part, to changes in testing practices. However a similar signal from wastewater analysis suggests that the decline was also due, in part, to a genuine decline in transmission (section 2.6).

Background

The effective reproduction number (*Rt*) represents the average number of people that one infected person can infect and the rate at which a disease spreads within a population at a specific point in time. This measure provides information on the impact of any public health measures in place.

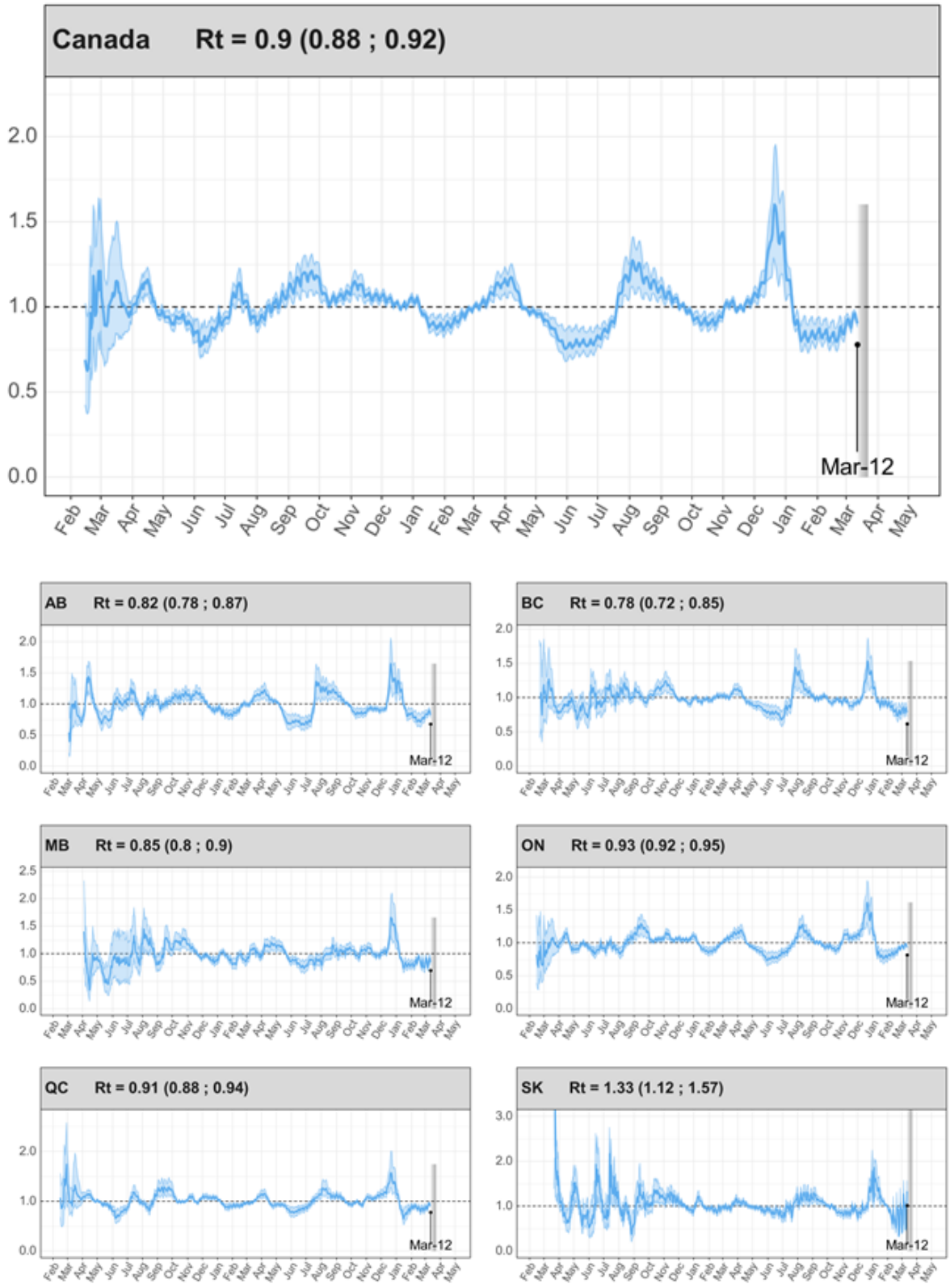
Method

The effective reproduction number *Rt* is calculated using the R package EpiEstim (version 2.2-3). The daily number of reported cases is used as a proxy for daily incidence. The number of reported cases for a particular day continue to be updated by the provinces and territories over several subsequent days. To avoid adding potentially misleading noise in the estimation of *Rt*, only data at least 11 days old are taken into account.

Results

National *Rt* based on date of onset was above 1 from end of August 2020 to early January 2021 indicating the epidemic was increasing. From mid-January to early March 2021, *Rt* was mostly below 1 indicating that nationally the epidemic was reducing. From March to April 2021, there was an increasing trend in *Rt* nationally and in most provinces. Nationally, *Rt* began to decrease in mid-April, but started to increase again at the end of June and was above 1 in July and the beginning of August. A declining trend has been observed from mid-August to September 2021; but it has been increasing and has been above 1 since mid-December. Decline in *Rt* in late December early January is likely to be due, in part, to changes in testing practices. However, a similar signal from wastewater analysis suggests that the decline is due, in part, to a genuine decline in transmission (Section 2.4). On March 12, 2022, Rt nationally was 0.9; and provincially was below 1 in all major provinces.

Figure 1. *Rt* estimates (with 95% confidence intervals) for Canada as a whole and individual provinces, from mid-February 2020 to March 12, 2022.



2.2 SHORT RANGE FORECAST OF REPORTED DEATHS IN CANADA BY THE GENERALIZED RICHARDS MODEL

Key points

- Short-range forecasts for cases were not produced given changes to testing protocols across Canada.
- Reported deaths on March 31, 2022 are projected to range from 37,347 to 37,601 (mean = 37,492).

Note: Supplemental information on methods and/or results for this report is provided in Annex 5.2.1.

Background

Phenomenological modelling approaches are used to project future cases and deaths in Canada in the near term. Future growth of the pandemic in Canada is based entirely on historic reported case counts (from https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection.html), and the models do not explicitly consider the mechanisms of transmission of COVID-19, including human behaviours and response to the pandemic (social distancing, facility closures and openings, vaccination, etc.) and recent introduction(s) of new SARS-CoV-2 variants to Canada. The models also do not account for any delays in testing, testing backlogs, changes to number of tests performed daily, changes to testing eligibility, etc. Nevertheless, unless extreme changes occur in the aforementioned variables, they can provide estimates of the trajectory of reported cases, and can be retroactively examined to identify apparent changes in trajectory.

Methods

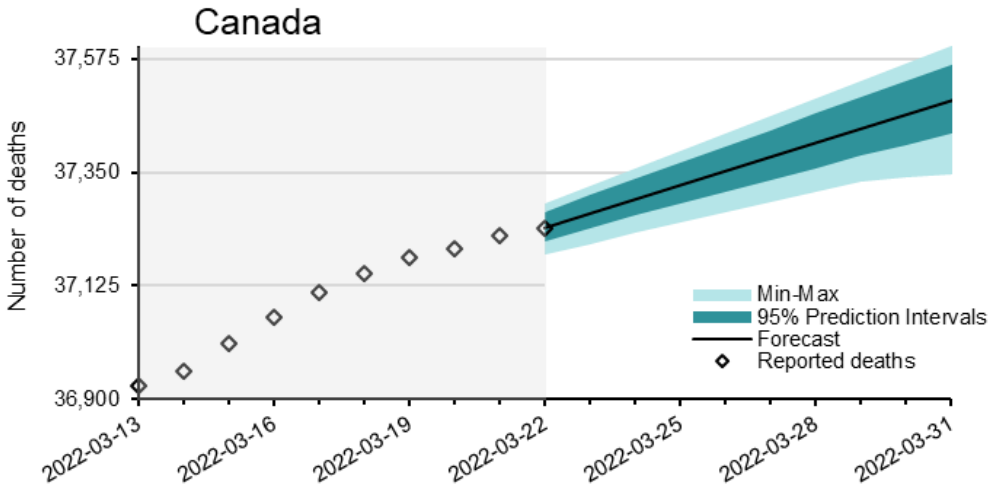
The Generalized Richards Model (GRM) (see Annex and https://doi.org/10.1016/j.epidem.2021.100457 for more description) was fit to Canadian death data up to and including March 22, 2022. Death projections were produced for Canada as a whole. Case projections were not completed given the changes made to testing eligibility in several provinces. The grey shaded area in each chart below indicates data reported prior to the projection date.

Projections produced for the last modelling report (using data through February 22, 2022) were hindered by lack of reporting over the holiday weekend in some provinces, and are therefore are not included.

Results

The incidence of new deaths is projected to remain steady throughout the next week in Canada.

Figure 1. Short range forecast for reported deaths in Canada.



2.3 LONG RANGE FORECAST OF REPORTED CASES AND HOSPITAL OCCUPANCY IN CANADA USING DYNAMIC MODELLING (PHAC-MCMASTER UNIVERSITY)

Key Points

- The long-range forecast suggests that, nationally, the number of COVID-19 infections and hospital admissions, as well as hospital occupancy rates will continue to decline, but will likely increase again with the lifting of restrictions.
- In April 2022, the number of hospital admissions and occupancy rates are forecast to be lower than January, with the possible exception of Alberta.
- Due to changes in data availability, there is significant uncertainty in these forecasts.

Note: Supplemental information on methods and/or results for this report is provided in Annex 5.2.2.

Background

A dynamic model accounting for the spread of variants of concern (VOCs) and vaccination is used to produce scenario-based forecasts of reported cases, hospital (acute-care; ICU are excluded) admissions and occupancy over the next 30 days. After a strong resurgence caused by the Omicron variant, reported cases, hospital occupancy have been declining in recent weeks. Many provinces have announced and begun lifting public measures since late January, early February and into March. In many provinces most restrictions have now been totally removed.

At the end of November 2021, a rapid surge of cases occurred as the Omicron VOC began to replace the Delta VOC-driven wave with similar growth patterns as that seen in the Republic of South Africa (RSA), and in many European countries. Compared to previous variants of SARS-CoV-2, Omicron is more transmissible, and can partly escape vaccine and post-infection immunity, which gives it a much greater advantage in spreading in the vaccinated as well as unvaccinated populations. By mid-December, testing capacities in most provinces had been reached, and testing strategies had to be adjusted, affecting the quality of surveillance data going forward. In addition to testing capacity, frequency of reporting also began to change and in February, Saskatchewan being the first jurisdiction to discontinue daily reporting on cases, and moved to weekly reporting. Other jurisdictions have subsequently either followed or announced plans to do so which has an increasing impact on data uncertainty going forward.

Methods

The PHAC-McMaster model is used to forecast cases by considering the effect of public health measures in mid-late December (prior to limitations on surveillance data due to the holiday season and changes in testing), ongoing vaccination efforts on SARS-CoV-2 transmission, and the expansion of the Omicron variant. Table A-1 (Annex 5.2.2) shows the key dates of recent measures that are included in the model for key provinces.

Three scenarios are considered here to reflect possible changes due to lifting measures that best fit the observed data:

1. Status quo – safe reopening which has minimal to no effect on the effective transmission rate.
2. Moderate reopening – causing a 2% increase in effective transmission rate.
3. Substantial reopening – causing a 4% increase in effective transmission rate.

Due to uncertainties in the reporting data streams, a sequential examination of when to place the changes in effective transmission in each province was conducted, starting from the most recent date of lifting of measures to best match the hospital occupancy data, accounting for expected delays in hospitalization and reporting.

To model the invasion of Omicron, this variant was estimated to be 2.4 times more transmissible than the Delta variant with a selection coefficient of 0.3/day (estimates from RSA, United Kingdom (UK) and the province of Ontario). The selection coefficient is how fast the invading VOC (Omicron) is dominating the resident (Delta) strain and translates to a doubling time in the odds of an infection being Omicron of approximately every 2.3 days. The Omicron invasion starts at 1% introduction in the last week of November for all provinces. This initial percentage is back-calculated from the preliminary estimate of S-gene target failures as of second week of December in Ontario at 20-40%.

The model includes vaccination (including boosters) following the observed daily administration rates for each province. Vaccine effectiveness (VE) against transmission is assumed to be 60% and 90% after the first and second dose, respectively, against the original variant (wild type) and the Alpha variant but decreased for the Delta VOC to 30% after the first dose and 80% after the second dose according to recent evidence. Boosters are assumed to maintain the second dose VE against infection for Delta. For Omicron, the VE is assumed to be reduced roughly by half of Delta, to 15% and 40% after first and second dose, respectively, and 70% after boosters. For the forecast, it is assumed that vaccination will continue according to a saturating function that resembles expected vaccine hesitancy (with a limit threshold of 95% first dose, 90% second dose and 85% boosters of the eligible population, now comprising all those in the 5 and above age group).

To reduce the risk of holiday effects and testing changes described in the background section, the model is calibrated with daily reported cases up to December 15, 2021 and hospital occupancies up to March 22, 2022 to account for the uncertainties due to under-reporting. Thus, the projections are the model expectations for reported cases if testing were unchanged/unrestricted and follow the expected patterns observed from the hospitalization dynamics accounting for delays, hospitalization rates and lengths of stay observed in Ontario and UK. To account for incidental hospitalizations (i.e. patients who test positive for COVID-19 on admission, but are admitted for reasons other than COVID-19), the model calibrates to expected hospitalization occupancy due to COVID-19, which is approximately 50-60% (observed by the Canadian Nosocomial Infection Surveillance Program) of reported hospital occupancies from early January.

Limitations

The national forecast is limited to the six major provinces. Due to surveillance limitations, changes in testing strategies, reporting frequency and reporting of primary cause of hospitalization, forecast uncertainties are large. Effects of new invading variants, such as Omicron BA.2 sub–lineage, are not included in the current model and forecast.

Results

The long-range forecast for reported cases (Figure 1) suggests the epidemic in Canada increased rapidly with the Omicron variant, but then declined, likely due to a combination of public health measures and post- vaccination and post-infection immunity, with a peak in mid-late January followed by a decline. There is some uncertainty in the relative contribution of immunity and public health measures in controlling the Omicron wave, particularly with the recent paucity of detailed case surveillance data. However, the reduction in growth, turnover and the magnitude in hospital occupancy (Figure 2) suggest the public health measures in place in late December were effective, accounting for lower hospitalization rates, shorter length of stay for Omicron cases, and proportion of incidental hospitalizations in the model. If public health measures were ineffective, a much higher and sharper increase in hospitalization would likely have occurred.

As the different jurisdictions lift public health measures, a resurgence in cases and hospitalizations is forecast. Most jurisdictions have been sequentially lifting public health measures from late January through to March. In many provinces most restrictions are now removed. Vertical lines in Figure 2 illustrate when public health measures were lifted. Solid, vertical green lines indicate lifting of public health measures effects of which would likely be detected by now in hospital occupancy data, and are therefore included in model fitting, and the last solid line is the change point for the forecast scenarios. Dashed, vertical green lines indicate lifting of public health measures effects of which would be unlikely as of yet to be detected in hospital occupancy data.

The hospital occupancy forecast (Figure 2) suggests a similar pattern to “cases” but with a flatter curve. This is because daily cases is an incidence metric whereas hospital occupancy is a prevalence metric. While the model calibrates to hospitalization with COVID-19, the projections adjust to overall occupancy which includes both those hospitalized for COVID-19 and incidental hospitalizations. While expected reported case projections cannot be validated with surveillance data, calibration to hospital occupancy observations provides evidence of the current/recent decline in infections. Similar to unrestricted reported case projections, hospital occupancies are projected to resurge but with much lower magnitude compared to previous waves and with stronger decoupling of infections and hospitalization. Recent data in the last week suggest the scenario with moderate effects of reopening (blue projections) matches observations most closely.

Lastly, leveraging the hospital occupancy calibration and evidence of shorter length of stay, Figure 3 shows the expected hospital admissions. As is the case for hospital occupancy, an increasing decoupling of cases and hospitalization is forecast due to increasing proportions of cases occurring in those with post-infection or post-vaccine immunity, who may acquire infection, but be unlikely to suffer severe outcomes that require hospital care.

Figure 1. Scenario-based forecast of reportable cases for the next 30 days for Canada and the major provinces. For each province, the red vertical lines indicate the implementation of public health measures at the end of December and green vertical lines indicates timing of lifting of restrictions as described in the main text. The black line shows the status quo (no increase in effective transmission), the blue line shows effects of moderate increases in transmission associated with reopening, and the red line shows effects of substantial increases in transmission. Shaded regions are the 95% prediction intervals. The grey region represents the approximate time of limited surveillance due to reduced testing and orange points are the recent surveillance data during this period.

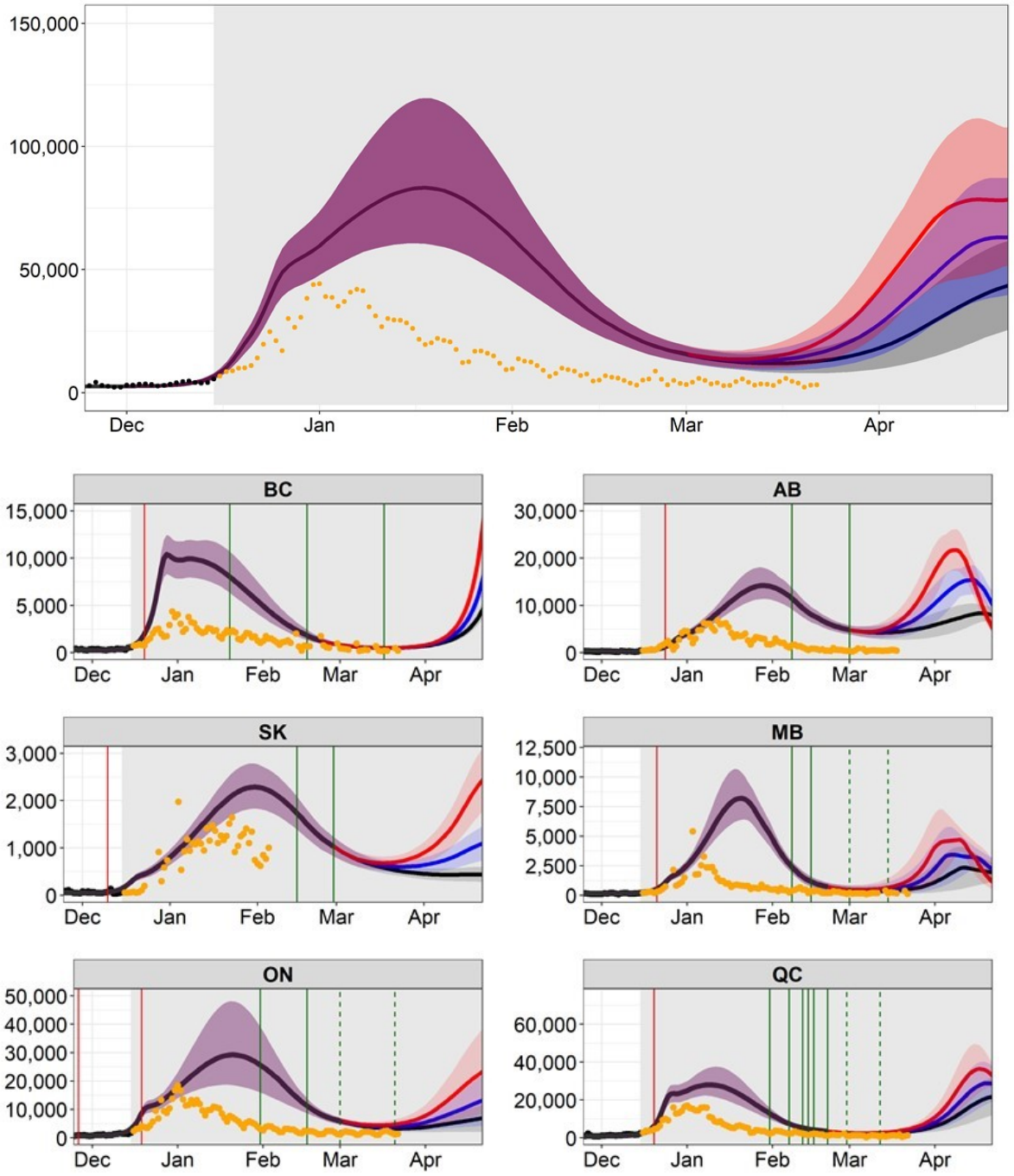


Figure 2. Scenario-based forecast of hospital occupancy for the next 30 days for Canada and the major provinces. Graphs of the scenarios, and other graph features, are as described in the caption for Figure 1. The black points are the daily observed hospital occupancy.

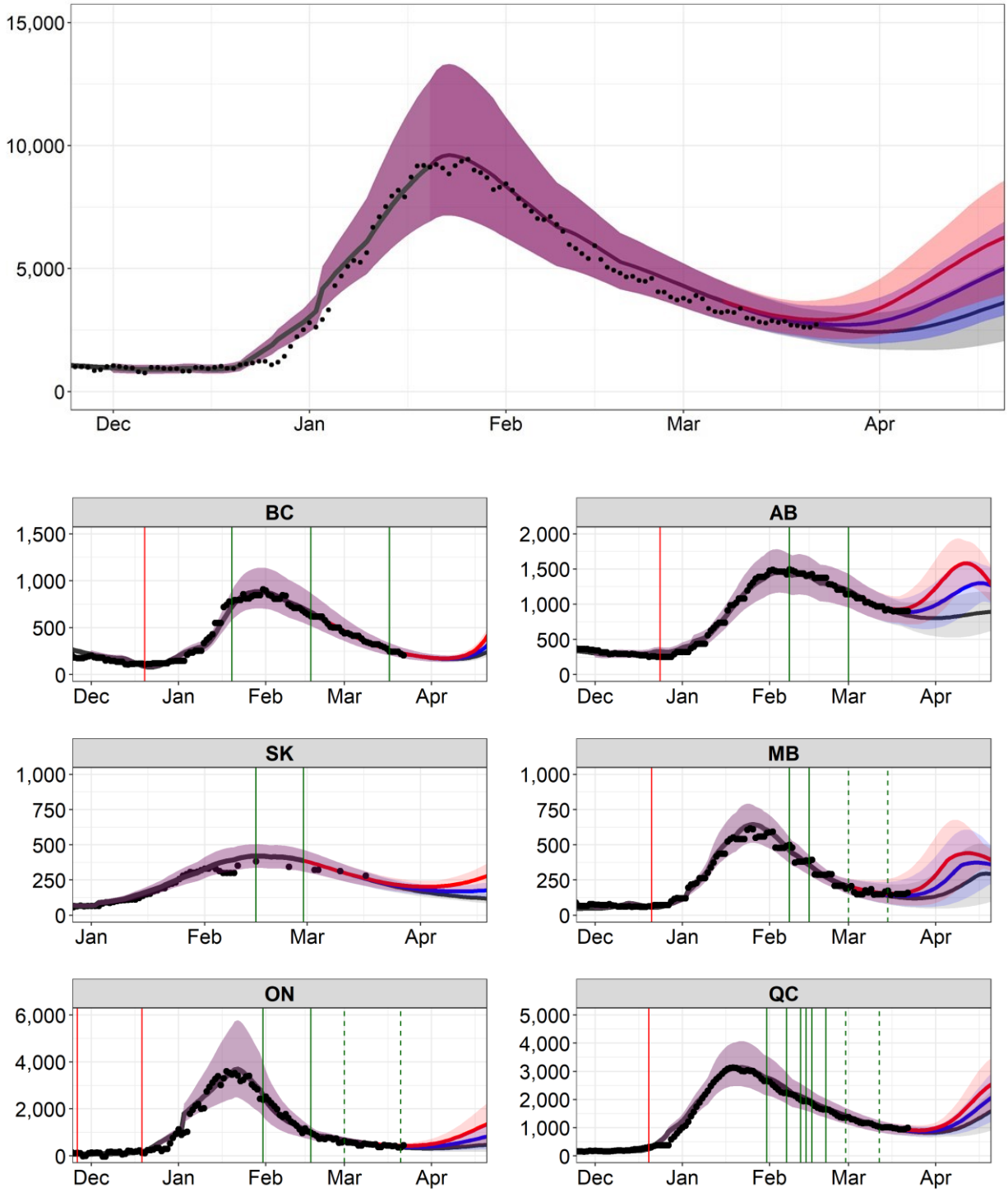
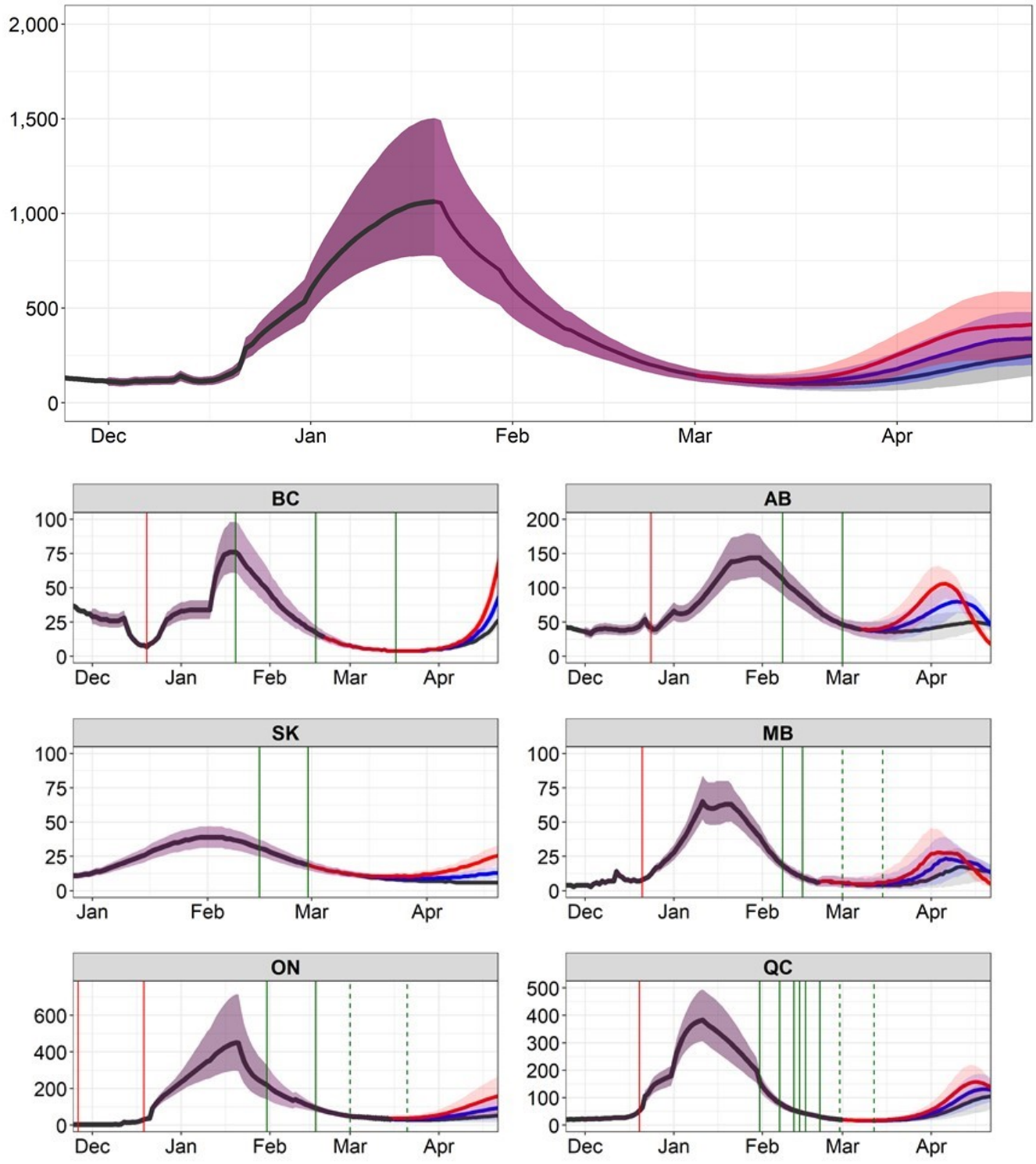


Figure 3. Scenario-based forecast of hospital admissions for the next 30 days for Canada and the major provinces. Graphs of the scenarios, and other graph features, are as described in the caption for Figure 1.



2.4 WASTEWATER SURVEILLANCE-BASED FORECASTS AND EFFECTIVE REPRODUCTION NUMBER ESTIMATES

Key points

- Since the Omicron peak, there has been an overall decreasing trend of COVID 19 in wastewater data.
- Under-reporting of clinical cases continues to decline.
- Case surveillance suggests a potential resurgence in some locations, but these are not yet confirmed by the wastewater data, which currently lags behind case data due to processing delays.

Background

As part of a pilot project led by Statistics Canada and the Public Health Agency of Canada (PHAC), wastewater from five cities across Canada (Vancouver, Edmonton, Toronto, Montreal and Halifax) has been sampled twice a week since October 2020 to assess and monitor the presence of SARS-CoV-2. RT-qPCR has been performed on wastewater samples to evaluate the concentration of SARS-CoV-2, as a proxy for the prevalence of infection in the communities included in the catchment areas of the wastewater treatment plants (WWTP).

Estimates of the effective reproduction number (*Rt*) and proportions of under-reported cases through clinical surveillance are reported by using wastewater data and the Wastewater Epidemic Model (WEM), a mathematical model developed by PHAC, which integrates SARS-CoV-2 concentration in wastewater along with traditional clinical data.

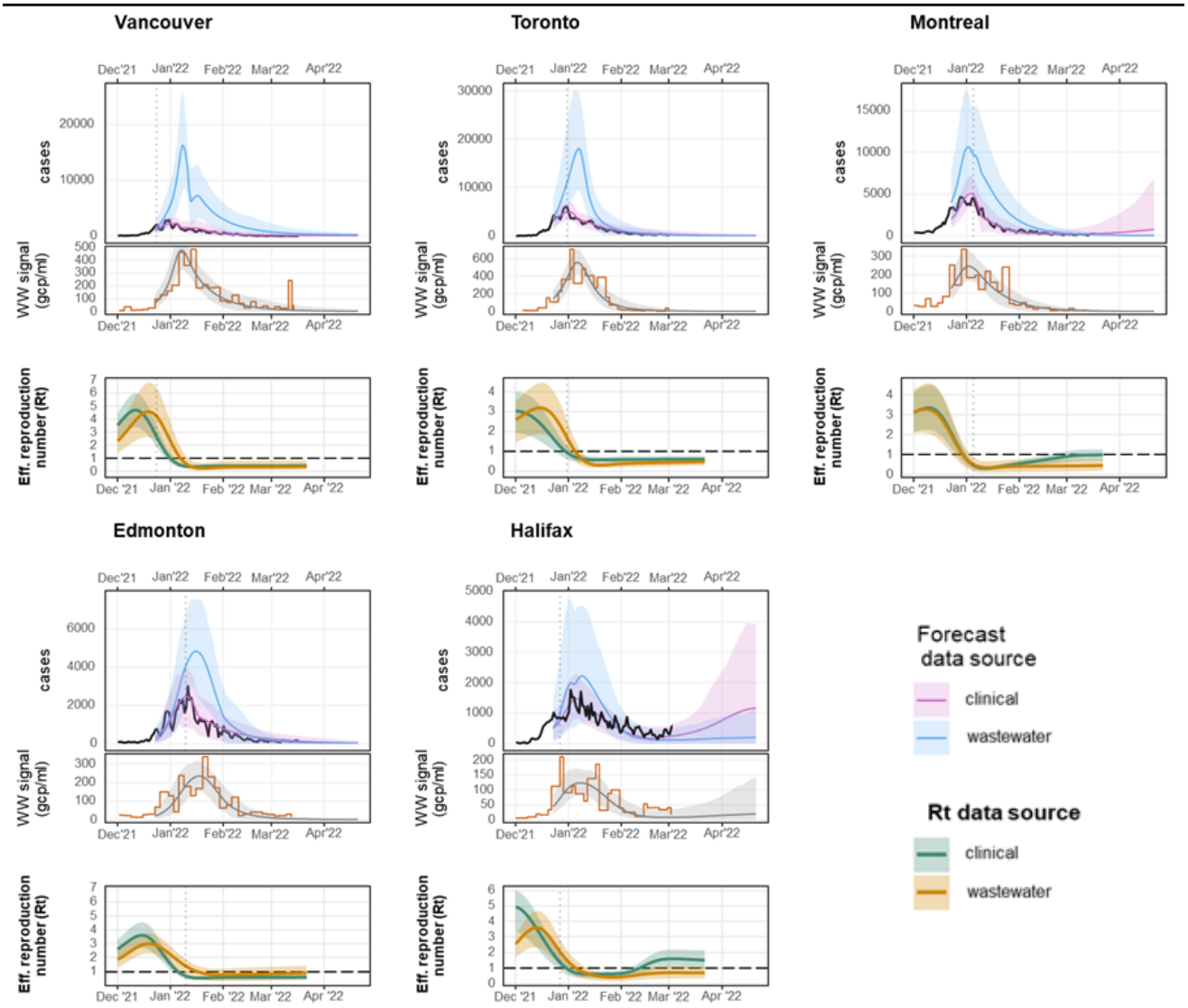
Methods

Reported cases for each sampling location were retrieved from the publicly available municipal dashboards. SARS-CoV-2 concentrations in wastewater measured for target gene N2 at each WWTP were retrieved. The epidemic model WEM (1,2) was fitted to reported cases and viral concentration in the wastewater separately for each sampling location and provided estimates of i) *Rt* and ii) the past and future, forecast numbers of reported cases. For reporting at the city level, a weighted average is calculated among all sampling locations in each city (the weights are proportional to the population size of the associated WWTP catchment area). Note: the potential impact of lifting public health measures remain mostly uncaptured in the forecasts.

Results

Figure 1 shows the *Rt* estimates and the inferred incidence for each city. In the top subpanel, for each city, the black curve displays the reported clinical cases (weighted average across sampling locations for each city). Fitting WEM to wastewater surveillance data, the blue curve indicates the number of cases that would have been reported, as well as the ones forecasted for future dates, if there were no limitations on the testing capacity. The pink curve shows the same inference, but when the model is fitted to reported case data only. In the middle subpanel, the orange step line shows the average SARS-CoV-2 concentration in wastewater across sampling locations for each city. The bottom subpanel display provides an estimate of *Rt* using either wastewater data only (brown curve) or reported case data only (green curve).

Figure 1. Forecasts and Rt estimates based on wastewater surveillance data and clinical reported cases. "Clinical" data are reported case data. In the top subpanel, for each city, the black curve displays the reported clinical cases (weighted average across sampling locations for each city). Fitting Wastewater Epidemiologic Model (WEM) to wastewater surveillance data, the blue curve indicates the number of clinical cases that would have been reported, as well as the ones forecasted for future dates, if there were no limitations on the testing capacity. The pink curve shows the same inference, but when the model is fitted to reported case data only. In the middle subpanel, the orange step line shows the average SARS-CoV-2 concentration in wastewater across sampling locations for each city. The bottom subpanel display provides an estimate of Rt using either wastewater data only (brown curve) or reported case data only (green curve).



The wastewater-based inference suggests that Toronto, Vancouver and Montreal had an under-reporting of approximately 50-70% of cases during the Omicron wave (the blue curve being substantially above the black and pink curves). Wastewater signals also support that an infection peak may have been reached late December

2021/early January 2022 in all five cities, as indicated by the shape of the (past and future) incidence estimated from wastewater data only (blue curves, top subpanels) and *Rt* below or close to a value of 1 (bottom subpanels).

The wastewater data, updated up to March 15, 2022, confirms the downwards trend of SARS-CoV-2 prevalence in the five cities. The clinical under-reporting appears to be declining, as indicated by the narrowing gap between the blue and pink curves in the upper panels of Figure 1.

The slight increase in reported cases in Montreal suggests a resurgence but this is not confirmed yet by the wastewater data, which lags about one week behind case data due to processing delays at present. Similarly in Halifax, reported cases suggest a resurgence not yet seen in wastewater surveillance. Note for this location, reporting is now weekly, not daily, so estimates should be taken with caution. Brief spikes in SARS-CoV-2 concentration in wastewater has been observed in Vancouver in mid-March, but they did not translate to a forecast or observed resurgence of cases.

References

1. Nourbakhsh, S et al. A Wastewater-Based Epidemic Model for SARS-CoV-2 with Application to Three Canadian Cities. MedRxiv. *https://www.medrxiv.org/content/10.1101/2021.07.19.21260773v1*
2. Model publicly available as an R package: *https://github.com/phac-nml-phrsd/wem*

3 INTERNATIONAL SITUATIONAL AWARENESS

3.1 IMPORTATION RISK BY AIR AND LAND

Key Points

- The highest expected importation risk by air is from Mexico and the highest risk by land is from the states of Washington and Michigan.
- From March 13 to 19, 2022, the estimated percentages of imported cases from air travel that may be variants of concern (VOCs) or variants of interest (VOIs) among all known sequenced strains are: 79.17% B.1.1.529 (Omicron), 19.82% BA.2 (Omicron), and 0.03% B.1.617.2 (Delta). Other VOIs/VOCs each represent less than 0.01% of imported cases.
- The four major airports in order of highest estimated importation risk are Toronto Pearson International, Montréal-Trudeau International, Vancouver International and Calgary International.

Note: Supplemental information on methods and/or results for this report is provided in Annex 5.2.3.

Background

The importation risk model estimates the mean weekly number of travellers arriving into Canada that are infected with COVID-19. Model estimates account for the volume of travellers (by air and land), country- and American state-specific weekly incidence rates, temporal infection dynamics, country-specific vaccine coverage and border measures (pre-arrival testing for non-essential travellers). The role of quarantine in Canada upon arrival to identify and contain infected travellers falls outside the scope of this work.

Methods

The importation risk model calculates the risk of importing COVID-19 at the daily level, and spatially for air and land ports of entry (PoEs). The estimate is a function of probabilities of exposure to COVID-19 given time spent since the start of the pandemic in the country of origin, or American State, for foreign travellers (FT). Additionally, for Canadians (CND), the estimate accounts for exposure in the country visited, or American state, before returning to Canada. Both air and land travel are considered.

The travel volume for each country or point of entry, for both land and air travel modes are provided by Canadian Border Services Agency (CBSA) from the Advanced Passenger Information (API) database at the weekly level. The model accounts for the proportion of non-exempt travellers (i.e. travellers who are not exempt from the pre-arrival PCR test, or, as of February 28, 2022, a rapid antigen test) who are fully, partially or not vaccinated, based on ArriveCAN and ContactTrace data. The proportion of non-exempt travellers who have received a booster dose is assumed to be proportional to the corresponding proportion in the country of origin. Since analogous data is not available for exempt travellers (as they are not required to provide proof of vaccination), the model assumes that the proportion of exempt travellers who are partially or fully vaccinated, or have received a COVID-19 booster is equal to the vaccine coverage in the country of origin (see Annex 5.2.3 for further details on methods). Following the vaccine mandate implemented on January 15, 2022, the majority of exempt land travellers and air FTs are

assumed to be either fully vaccinated or boosted, the proportion of which mirrors the country-specific vaccination levels.

Importation risk estimates are stratified by variants of concern (VOC) and variants of interest (VOI) as reported by the United States of America (USA) Centers for Disease Control and Prevention. It is assumed that the proportion of variants reported in the GISAID database for the embarkation location during a three-week period (which includes the week modelled and the two prior weeks) is the same proportion that would be observed in infected travellers arriving in Canada from these countries or American states. Outputs for this report are restricted to countries with at least 20 sequenced samples (Table A-2 in the Annex 5.2.3). Reported results show the number of infected passengers stratified by VOC/VOI where these data are present, "other" for non VOC/VOI, and "unknown" if the number of sequenced samples for the country is below 20, including no sequenced results.

A semi-Bayesian method, adapted from [1], was used to calculate a time-varying correction factor for the country specific case count. The method, which is described in the annex, uses the reported number of COVID-19 tests and the temporal changes in the susceptible population size due to increasing cumulative case counts and vaccination rates to estimate the actual number of cases for each country.

It is assumed that the Omicron variant became the dominant variant on December 1, 2021. The immune escape properties of the Omicron variant are modelled by decreasing the vaccine efficacies against infection, and by assuming that only 35% of people infected with COVID-19 prior to December 2021 remain immune to reinfection, thus increasing the size of the susceptible population used to calculate the time-varying correction factor, and the probability of infection (see Annex 5.2.3 for further details). Given the rapid spread of the Omicron variant, the testing capacity has been overwhelmed in many jurisdictions, impacting global case count and testing data estimates. The resulting paucity of data could result in an underestimation of the model results during the Omicron wave, while the country-level underestimation of the number of people previously infected with Omicron (i.e. immune population), could cause a subsequent overestimation of the model results.

Note: Due to data unavailability, ArriveCan and ContactTrace data from March 6 to 12, 2022 was used to estimate the non-exempt travel volume, the proportion of travellers exempt from showing proof of vaccination, and the vaccine status distribution for non-exempt travellers.

Results

Air travel

National level

A mean of 2,944 infected travellers were expected to arrive in Canada by air for the week of March 13 to 19, 2022. Mexico is estimated to contribute the highest importation risk to Canada, followed by the USA and Germany (Figure 1). For the top 10 countries estimated to contribute infected travellers, the percent contribution from VOC and VOI among all known sequenced strains are 79.17% B.1.1.529 (Omicron), 19.82% BA.2 (Omicron), and 0.03% B.1.617.2 (Delta). Other VOIs/VOCs each represent less than 0.01% of imported cases.

Compared to the Global Public Health Intelligence Network (GPHIN), which obtains information from open-source media reports and the World Health Organization (WHO) weekly epidemiological report, it has been noted that some data might not be available in the GISAID database. Therefore, VOC and VOI data obtained from GISAID (Figure 1) may underestimate the importation of VOCs and VOIs.

Regional level

The proportion of infected travellers entering Canada varies by airport and traveller status. The percent positive among those required to provide a negative PCR test result prior to departure (non-exempt) was smaller than the percent positive among those who were not required to provide a negative PCR test result prior to departure (exempt) (Table 1). The countries contributing infected travellers vary for the four major Canadian airports receiving international travellers for the week of March 13 to 19, 2022. The Omicron variant comprises the majority of imported cases (Figure 2).

Figure 1. Estimated distribution of variants for the top 10 countries expected to have contributed infected air travellers (via direct and indirect flights) into Canada for the week of March 13 to 19, 2022.

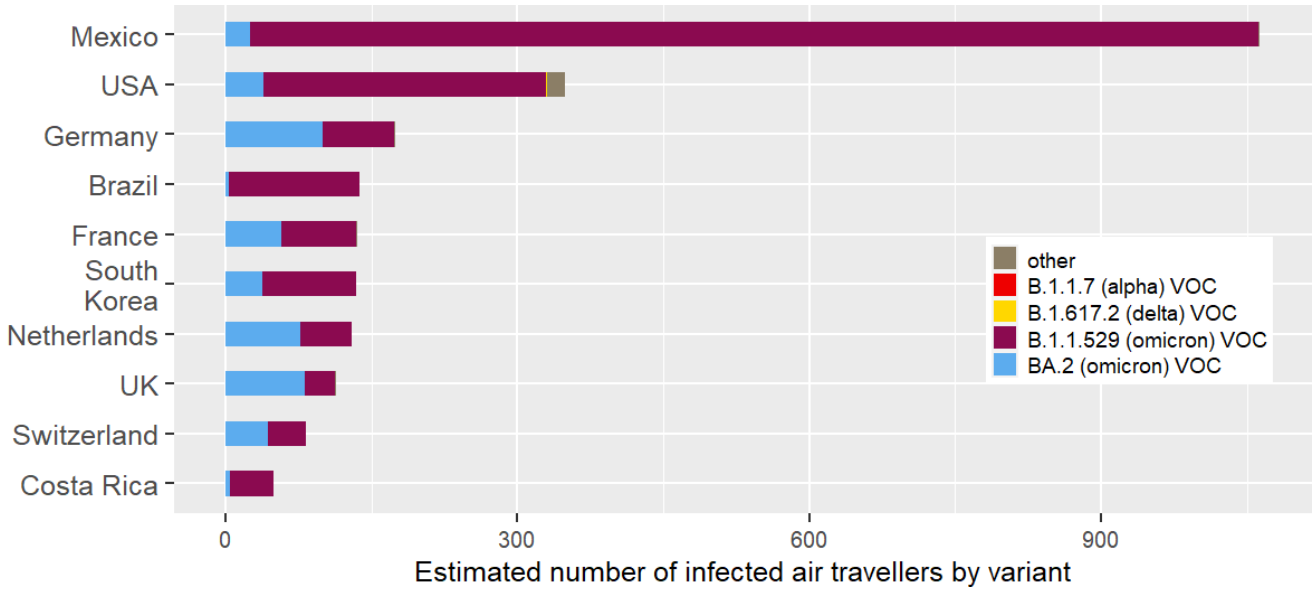
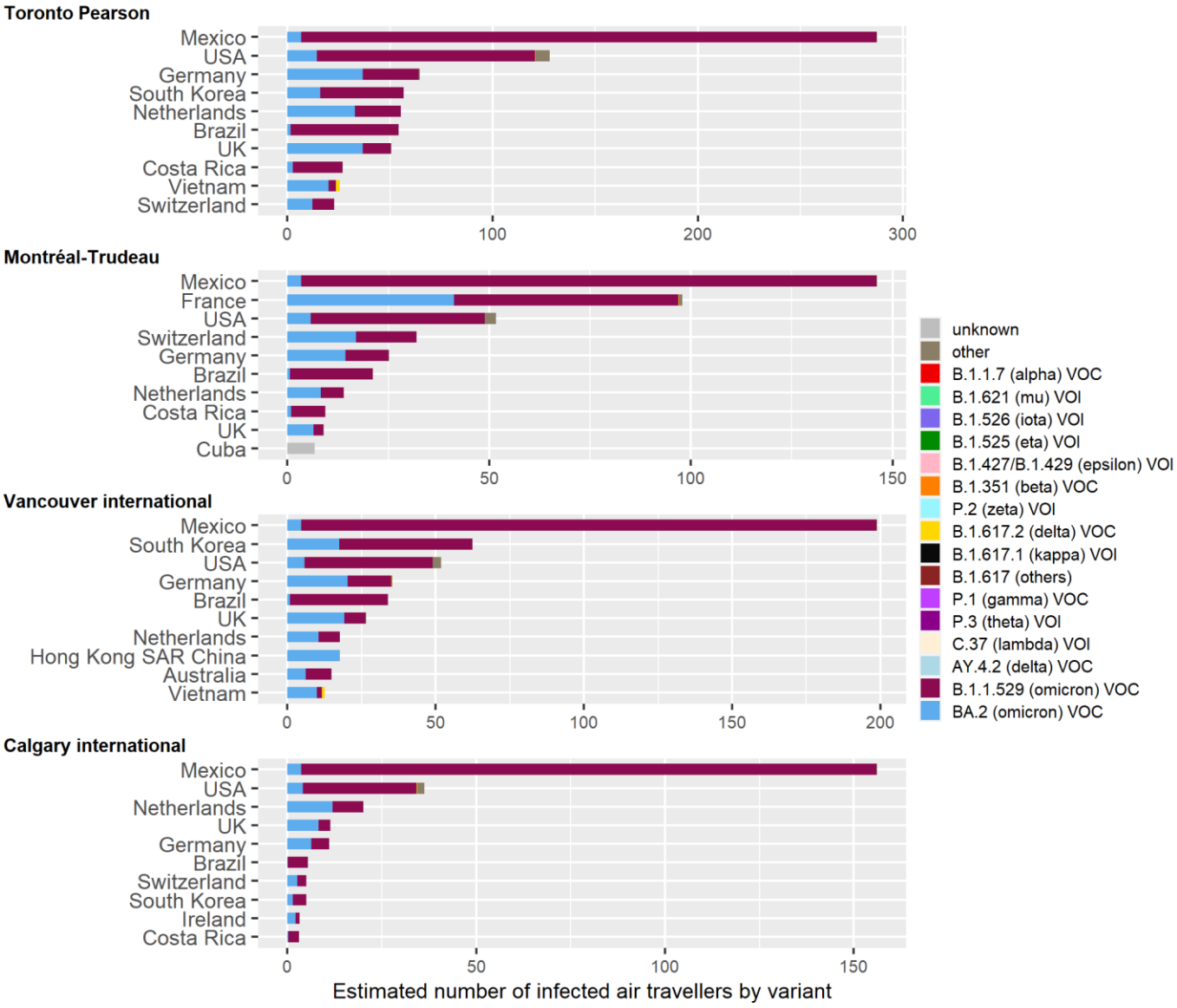


Table 1. Number and proportion of infected travellers arriving at major Canadian airports, stratified by traveller status for the week of March 13 to 19, 2022.

Airport	Traveller status	Mean infected travellers	Weekly travel volume	Percent positive (%) (simulation results)
Toronto Pearson	Non-exempt	834.2	141,387	0.59
	Exempt	193.7	14,801	1.31
	Total	1,027.9	156,188	0.66
Montréal-Trudeau	Non-exempt	412.4	62,754	0.66
	Exempt	82.7	6,686	1.24
	Total	495.1	69,441	0.71
Vancouver International	Non-exempt	451.3	48,779	0.93
	Exempt	106.3	5,493	1.94
	Total	557.6	54,273	1.03
Calgary International	Non-exempt	243.9	30,575	0.80
	Exempt	35.9	3,098	1.16
	Total	279.9	33,673	0.83

Figure 2. Estimated distribution of variants for the top 10 countries expected to have contributed to infected air travellers into the four main Canadian airports for the week of March 13 to 19, 2022.



Land travel

A mean of 1,274 infected travellers were expected to arrive in Canada by land for the week of March 13 to 19, 2022. The mean number of infected travellers predicted to arrive at land PoEs from the USA is highest for British Columbia (Table 2). Most infected land travellers are estimated to arrive in Canada from Washington and Michigan states (Table 3). The estimated importation of variants arriving in a province is proportional to the variants reported in GISAID at the state level for the state adjoining the land PoE (Table 4).

Table 2. Mean number of infected travellers arriving in Canada by land from the USA, as summarised by province, for March 13 to 19, 2022.

Province	Mean estimated infected travellers	Standard deviation	Weekly travel volume	Percent positive (%)
British Columbia	641.9	17.1	75,698	0.85
Ontario	441.8	9.2	255,174	0.17
Quebec	79.3	1.4	38,784	0.20
New Brunswick	45.8	1.0	13,477	0.34
Alberta	32.9	1.7	8,150	0.40
Manitoba	15.5	0.6	11,944	0.13
Saskatchewan	13.6	0.7	4,720	0.29
Yukon	2.8	0.2	366	0.77

Table 3. Mean number of infected travellers arriving in Canada by land as summarised by the last US state before entry into Canada, for March 13 to 19, 2022.

State	Mean estimated infected travellers	Standard deviation	Weekly travel volume	Percent positive (%)
Washington	520.34	16.12	69,833	0.75
Michigan	259.59	8.42	129,262	0.20
New York	207.31	3.78	142,907	0.15
Idaho	104.16	4.52	2,558	4.07
Maine	55.85	1.19	15,908	0.35
Montana	41.09	1.68	10,300	0.40
Vermont	37.49	1.08	15,470	0.24
North Dakota	24.03	0.81	9,372	0.26
Minnesota	9.03	0.32	4,706	0.19
Alaska	6.66	0.24	866	0.77
New Hampshire	0.04	0.01	16	0.25

Table 4. Mean number of infected travellers for VOCs and VOIs with an expected percent positivity higher than 0.001%, for March 13 to 19, 2022.

PT	Weekly travel volume	Variant	Mean estimated infected travellers	Standard deviation	Percent positive (%)
ON	255,174	B.1.1.529 (Omicron) VOC	338.42	7.0	0.1326
		BA.2 (Omicron) VOC	61.83	1.2	0.0242
BC	75,698	B.1.1.529 (Omicron) VOC	553.10	14.6	0.7307
		BA.2 (Omicron) VOC	81.02	2.3	0.1070
QC	38,784	B.1.1.529 (Omicron) VOC	62.40	1.1	0.1609
		BA.2 (Omicron) VOC	15.96	0.3	0.0412
NB	13,477	B.1.1.529 (Omicron) VOC	41.76	1.0	0.3098
		BA.2 (Omicron) VOC	3.75	0.1	0.0278
MN	11,944	B.1.1.529 (Omicron) VOC	14.51	0.5	0.1214
		BA.2 (Omicron) VOC	0.86	0.0	0.0072
AB	8,150	B.1.1.529 (Omicron) VOC	29.76	1.5	0.3652
		BA.2 (Omicron) VOC	3.05	0.2	0.0375
SK	4,720	B.1.1.529 (Omicron) VOC	12.66	0.7	0.2682
		BA.2 (Omicron) VOC	0.83	0.0	0.0175
YK	366	B.1.1.529 (Omicron) VOC	1.69	0.1	0.4610
		BA.2 (Omicron) VOC	1.14	0.1	0.3125

References

1. Wu, S.L., et al., *Substantial underestimation of SARS-CoV-2 infection in the United States.* Nature communications, 2020. **11**(1): p. 1-10.

3.2 COMPARING PUBLIC HEALTH MEASURES IN CANADA AND OTHER COUNTRIES

Key points

- In Canada, with the rise of Omicron cases in late December 2021, the stringency index increased to 78. Following the progressive decline in the number of cases, the index reduced to 69.
- Internationally, disease activity greatly varies across many countries: many countries have eased public health measures based on current COVID-19 trends, health care capacity, and vaccine coverage, while some have maintained or re-implemented measures.

Background

The stringency index is a semi-quantitative combination of information from nine different public health interventions: school closing, workplace closing, cancelling public events, restrictions on gathering size, closing public transport, stay at home requirements, restrictions on internal movement, restrictions on international travel, and public information campaigns. This index is mapped with COVID-19 disease outcome data from other countries to flag interventions that could be having an effect. The figures in this report show the current epidemiological situation, in Canada and selected other countries, alongside the level of stringency index (termed "Government Response" or "Interventions" in figures) and where appropriate, information on vaccinations administered.

Method

International

COVID-19 surveillance data are from Our World in Data (OWID; University of Oxford) (https://ourworldindata.org/coronavirus), except for Canada, which are from the Public Health Agency of Canada/Infobase (*https://health-infobase.canada.ca/COVID-19/*) and from provincial and territorial website data. COVID-19 surveillance data are mapped with public health intervention data from the Government Response Tracker (University of Oxford - *https://www.bsg.ox.ac.uk/research/research-projects/coronavirus-government-response-tracker*). Additionally, information from Our World in Data (University of Oxford) on vaccinations is included.

Provincial/territorial

COVID-19 surveillance data are from the Public Health Agency of Canada/Infobase and from provincial and territorial website data, and public health intervention data are primarily from data mining and coding of publicly available information by the Public Health Agency of Canada. Starting in early-September 2021, some provinces began implementing public health measures dependent on vaccination status of the population; referred to in this report as "vaccine proof". For example, individuals that are not fully vaccinated cannot enter certain businesses (e.g. casinos or restaurants) and are unable to attend public events (e.g. concerts). These restrictions do not apply to fully vaccinated individuals. Considering these recent changes, coding of provincial/territorial public health intervention data in regions where vaccine proof is required is based on the restrictions in place for

the unvaccinated individuals rather than the less stringent measures applicable for fully vaccinated individuals. This approach is consistent with other previous methodological decisions and will be applied consistently.

The main purpose of combining these sources of information is to identify interventions that could be having an effect, in combination with vaccine roll-out, in controlling the COVID-19 pandemic. Experiences both in Canada and in other countries show that government measures have three critical elements: how "strict" the government measures were (stringency index), timing - when the government measures were implemented/relaxed and duration - how long the measures have been in place. A fourth important element, compliance or adherence, is not addressed in these datasets.

Note: The stringency index data used for Canada is collected externally by Oxford using a defined methodology. The approach to determining stringency at the provincial / territorial level is based on the Oxford methodology but with some differences to provide a more accurate picture of public health measures within the Canadian context. Therefore, direct comparisons between provinces / territories and the Oxford-derived stringency index for Canada should be made with caution.

Results

National and international

The situation in Canada is included alongside countries that are experiencing or have experienced a steep rise in Omicron cases (Table 1, Figure 1). Although testing volumes remain at high levels, capacity relative to the true number of cases as well as testing eligibility has changed over time and by jurisdiction. Therefore, surveillance data now significantly underestimate the true incidence of infection. Given the current limitations and the need for caution in the interpretation of case surveillance data, this report focuses on the experiences of other countries in re-implementation, and now in some instances, the subsequent easing of public health measures, increasing vaccine coverage and expanding booster dose eligibility.

Table 1. Canada and selected other countries; weekly rolling average of daily cases and deaths of COVID-19/100,000, weekly rolling average of percent test positivity, number of patients in hospital/100,000, vaccination coverage and information on containment and health interventions (as of March 21, 2022, unless otherwise indicated).

Country as sorted by weekly rolling average of daily cases	Weekly rolling average of daily cases/100,000**	Weekly rolling average of percent (%) test positivity	Number of patients in hospital/ 100,000**	Weekly rolling average of daily deaths/ 100,000**	Percent (%) of entire population fully vaccinated	Percent (%) of entire population with a booster	Stringency index
South Korea	754 (↑)	86%	NA	0.6	87%	63%	41 (Mar 20)
Hong Kong	272 (↓)	NA	NA	3.5	72%	30%	75 (Mar 12)
Germany*	228 (↑)	53% (Mar 13)	NA	0.2	75%	58%	79 (Mar 20)
Australia*	191 (↑)	47%	8	0.1	81%	49%	54
France	133 (↑)	26% (Mar 17)	31	0.2	78%	54%	19
United Kingdom	131 (↑)	11% (Mar 18)	23	0.2	72%	57%	27 (Mar 18)
Denmark	127 (↓)	24%	23	0.6	81%	62%	14 (Mar 18)
Italy*	117 (↑)	16%	15	0.2	79%	64%	64 (Mar 18)
Israel*	93 (↑)	14%	10	0.1	66%	56%	18
Japan*	37 (↓)	35%	16 (Mar 16)	0.1	80%	35%	47
Spain*	31 (↓)	18% (Mar 18)	9	0.2	86% (Mar 16)	52% (Mar 16)	44 (Mar 15)
Canada	**14 (stable) (Mar 20)**	**14% (Mar 18)**	**10 (Mar 20)**	**0.1 (Mar 20)**	**81% (Mar 13)**	**46% (Mar 13)**	**69 (Mar 11)**
United States*	9 (↓)	2% (Mar 15)	5	0.3	65% (Mar 20)	29%	59 (Mar 16)
South Africa*	2 (↓)	6%	NA	<0.1	29%	3%	38 (Mar 15)
China*	0.2 (↑↑)	NA	NA	<0.1	86%	46%	64 (Mar 01)

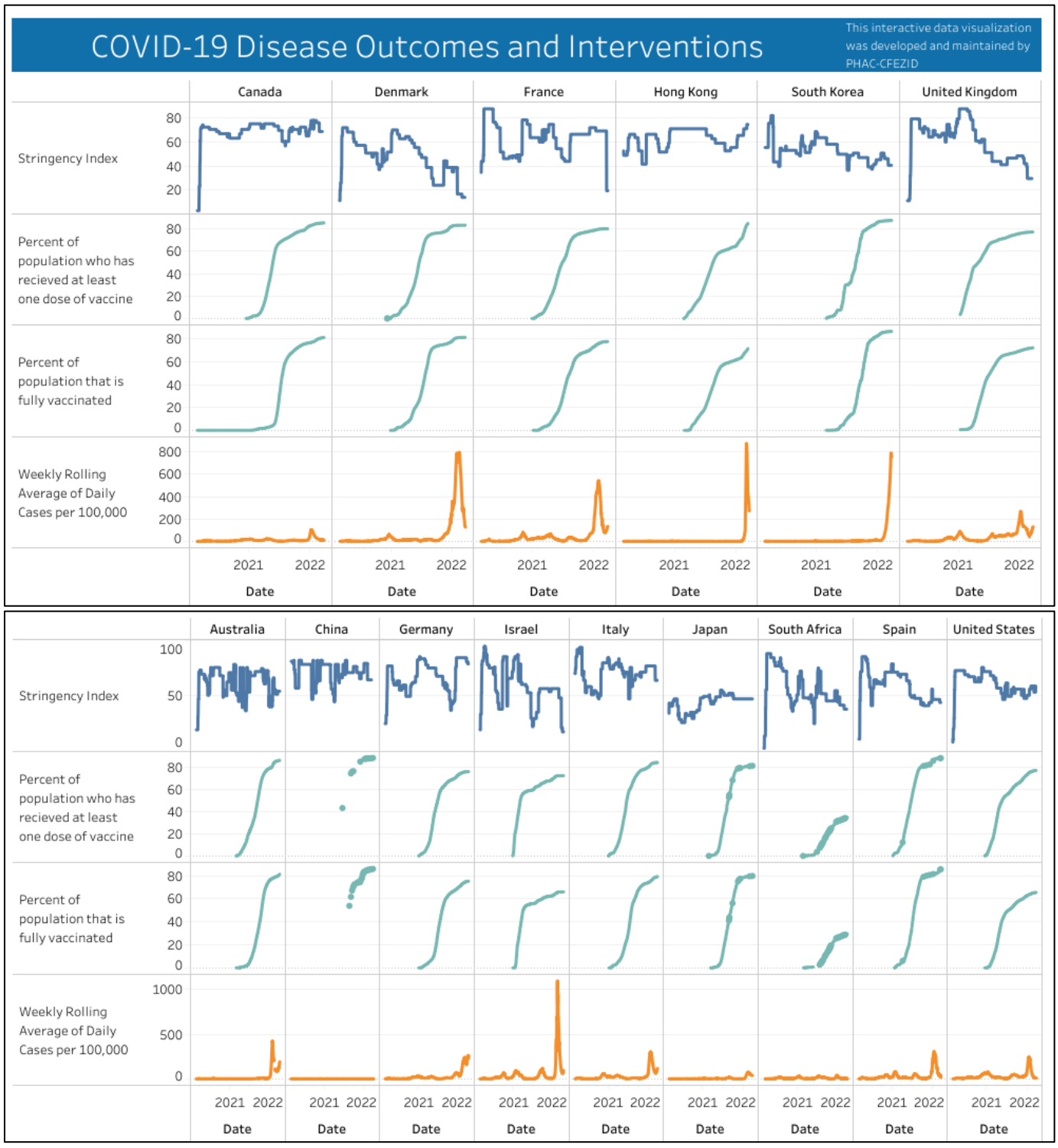
* Indicates country with no descriptive summary; data are only provided in Table 1 and Figure 1 for reference purposes.

** Cases and deaths data include data from 9 of Canada's 13 provinces and territories; hospital data include data from 7 of Canada's 13 provinces and territories ↓ = Decrease compared to previous 14 days' weekly rolling average; ↑ = 10-100% increase compared to previous 14 days' weekly rolling average; ↑↑ ≥ 100% increase compared to previous 14 days' weekly rolling average (as per the March 21, 2022 Trend Report; these numbers may differ from those produced on other dates). NA = Data unavailable

Data source: Oxford University. Our World in Data. Accessed on: 2022-03-22. Available at: https://ourworldindata.org/coronavirus.

Data on the percent of the population fully vaccinated in Canada were sourced from the COVID-19 Canada Open Data Working Group. Accessed on 2022-03-22. Available at: https://opencovid.ca/. Data on the weekly rolling average of cases and deaths in Canada were sourced from provincial and territorial websites. Accessed on 2022-02-22. Data on the weekly rolling average of percent test positivity were sourced from SALT. Accessed on 2022-02-22.

Figure 1. Canada and selected other countries; weekly rolling average of daily cases of COVID-19/100,000, and vaccination coverage and information on containment and health interventions.



Data source: Oxford University. Our World in Data. Accessed on: 2022-03-22. Available at: https://ourworldindata.org/coronavirus.
Data on the percent of the population fully vaccinated in Canada were sourced from the COVID-19 Canada Open Data Working Group. Accessed on 2022-03-22. Available at: https://opencovid.ca/. Data on the weekly rolling average of cases and deaths in Canada were sourced from provincial and territorial websites. Accessed on 2022-02-22.

Canada

Cases: Since peaking on January 2, 2022, the weekly rolling average of cases has decreased and is now at levels consistent with May 2021.

Test Positivity: The weekly rolling average of test positivity remains elevated and has shown signs of increasing.

Deaths: Since peaking on January 26, 2022, the weekly rolling average of deaths has decreased.

Vaccination: As of March 21, 2022, 48% of the entire population has received a booster dose.

Public Health Measures: The current stringency index is 69, as of March 11, 2022; this value has been in place since February 21, 2022. Despite many jurisdictions easing province- or territory-wide public health measures over the last month, there has been no change in the Oxford-collected stringency index.

South Korea

Cases: Case incidence began increasing in mid-January 2022 and is now at levels not previously seen.

Test Positivity: The weekly rolling average of test positivity remains elevated and is increasing.

Deaths: As with cases, the weekly rolling average of deaths is now at levels not previously seen and continues to increase.

Vaccination: As of March 21, 2022, 63% of the entire population has received a booster dose.

Public Health Measures: The current stringency index is 41, as of March 20, 2022; this value has been place since March 1, 2022. Changes to public health measures in the last month include:

- On March 2, 2022, the vaccine proof policy was removed which resulted in a move from requirements to recommendations for public events.

As of March 20, 2022, current public health measures in place include:

- Workplaces: Reduced hours and social distancing measures in place.
- Public events: Permitted with social distancing measures in place.
- Gatherings: Limits on private gatherings of 10 people or less.

Hong Kong

Cases: Since peaking on March 4, 2022, the weekly rolling average of cases has rapidly decreased but still remains at elevated levels.

Test Positivity: There is limited data on test positivity in OWID; according to a situational report released by Hong Kong, test positivity ranged from 1-12% across Hong Kong's residential districts on week 12 of 2022 (week ending on March 19, 2022) [1].

Deaths: As with cases, the weekly rolling average of deaths is now at levels not previously seen with very early indication of peaking.

Vaccination: As of March 13, 2022, 30% of the entire population has received a booster dose.

Public Health Measures: The current stringency index is 75, as of March 12, 2022; this value has been place since March 7, 2022. Changes to public health measures in the last month include:

- On February 16, 2022, all mass events were cancelled.
- On February 24, 2022, a vaccine proof policy was implemented for access to most public facilities and events.
- On March 7, 2022, schools were closed for a special vacation.

As of March 12, 2022, current public health measures in place include:

- Schools: Closed for a special vacation.
- Workplaces: Non-essential businesses closed.

- Public events: Large events are not permitted, and masks are required for smaller events (which also have limits on size).
- Gatherings: Restrictions on gatherings of 10 people or less.
- Public transport: Masks required.
- Stay-at-home orders: Although no formal stay-at-home orders are in effect, it is strongly recommend to work from home where possible.
- Internal movement: Recommendations for limiting non-essential travel and working from home where possible.

France

Cases: Since peaking on January 26, 2022, the weekly rolling average of cases has rapidly decreased however in the last two weeks cases have been observed to have changed trajectory.

Test Positivity: Similar to cases, since peaking on January 11, 2022, the weekly rolling average of test positivity decreased however in the last two weeks there has been observed to have changed trajectory.

Deaths: Since peaking on February 10, 2022, the weekly rolling average of deaths has decreased.

Vaccination: As of March 21, 2022, 54% of the entire population has received a booster dose.

Public Health Measures: The current stringency index is 19, as of March 12, 2022; this value has been place since March 14, 2022. Changes to public health measures in the last month include:

- On March 14, schools moved to level 1 of their health protocol.
- On March 14, the vaccine proof policy was removed and restrictions on use of face masks were eased in many indoor locations.

As of March 14, 2022, current public health measures in place include public health information campaigns and international travel controls.

United Kingdom

Cases: Following an unprecedented increase in cases and a peak observed in early-January 2022, cases changed trajectory and started to decline, however cases have been increasing since end-February 2022.

Test Positivity: Test positivity has increased over the last two weeks.

Deaths: Since peaking in mid-January, the weekly rolling average of deaths decreased and has plateaued in the last two weeks.

Vaccination: As of March 21, 2022, 57% of the entire population has received a booster dose.

Public Health Measures: The current stringency index is 30, as of March 14, 2022; this value has been place since February 15, 2022.

As of March 14, 2022, current public health measures in place include:

- Schools: Schools in Scotland retain the masking requirement.
- Workplaces: All businesses are open, without any requirement to present vaccine proof. Organizations can choose to ask for vaccine proof. Workers are no longer advised to work from home. Masks no longer mandated in England, however are required in Scotland, and in some settings in Wales.
- Public events: No capacity restrictions or vaccination proof required (organizations can choose to ask for vaccine proof).

Denmark

Cases: Since peaking in February 2022, the weekly rolling average of cases continues to decrease.

Test Positivity: The weekly rolling average of test positivity remains elevated and is decreasing.

Deaths: As with cases, the weekly rolling average of deaths is now at levels not previously seen and continues to increase.

Vaccination: As of March 21, 2022, 62% of the entire population has received a booster dose.

Public Health Measures: The current stringency index is 14, as of March 18, 2022; this value has been place since March 1, 2022. On February 1, 2022, most domestic public health restrictions were lifted in Denmark. Changes to public health measures in the last month include:

- On March 1, 2022, international travel control measures were eased.

As of March 1, 2022, there are currently only recommendations for infection prevention in place in specific settings.

Within Canada

All provinces and territories experienced increases in COVID-19 incidence between December 2021 and January 2022 to levels previously unseen. However, all provinces and territories have since observed decreases in reported cases, with some jurisdictions noting increasing case counts in recent weeks. Significant strain on PCR-based test capacity has resulted in prioritization of specific populations for testing and case data now underestimates the true incidence of infection. See Table 1 and Figure 2.

British Columbia

Cases: Since peaking in early-January 2022, the weekly rolling average of cases has decreased.

Deaths: Since peaking in February 2022, the weekly rolling average of deaths has decreased.

Vaccination: As of March 13, 2022, 48% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 42, as of March 18, 2022; this value has been in place since February 17, 2022. Changes to public health measures in the last month include:

- Although the stringency index did not change in the last month, on March 10, 2022, British Columbia removed mask mandates for most settings and eased restrictions for some public events and gatherings.

As of March 18, 2022, current public health measures in place include:

- Schools: Mask mandates are in effect.
- Workplaces: There are no mask mandates, however the vaccine proof policy is still in effect.
- Public events: The vaccine proof policy is still in effect.
- Internal movement: At least one First Nations community has prohibited travel to and from the community.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains (*e.g.* regular COVID-19 updates and briefings).

Alberta

Cases: Since peaking in mid-January 2022, the weekly rolling average of cases has decreased. However, in the last week there has been an observed increase in the weekly rolling average of cases.

Deaths: Since peaking in mid-February 2022, the weekly rolling average of deaths has decreased.

Vaccination: As of March 13, 2022, 36% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index (SI) is 20, as of March 18, 2022; this value has been in place since March 8, 2022. Changes to public health measures in the last month include:

- On March 1, 2022, Alberta lifted school restrictions, workplace restrictions, restrictions on public events and gatherings, and mask mandates (however, regional mask mandates remained). (SI 44 to 23)
- On March 8, 2022, regional mask mandates were lifted. (SI 23 to 20)

As of March 18, 2022, current public health measures in place include:

- Workplaces: Some workplaces (*e.g.* healthcare settings) require masks; mask mandates have been removed elsewhere, as has the vaccine proof policy.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

Saskatchewan

Cases: Since peaking in late-January 2022, the weekly rolling average of cases has decreased.

Deaths: Since peaking in early-March 2022, the weekly rolling average of deaths has decreased but has been observed to be fluctuating in the past week.

Vaccination: As of March 13, 2022, 41% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 17, as of March 18, 2022; this value has been in place since February 28, 2022. Changes to public health measures in the last month include:

- As of February 28, 2022, provincial mask mandates were lifted in Saskatchewan. (SI 30 to 17)

As of March 18, 2022, current public health measures in place include:

- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

Manitoba

Cases: Since peaking in mid-January 2022, the weekly rolling average of cases has decreased. However, in the last week, there has been an observed stabilization in cases.

Deaths: Since peaking in late-January 2022, the weekly rolling average of deaths has decreased.

Vaccination: As of March 13, 2022, 42% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 58, as of March 18, 2022; this value has been in place since March 15, 2022. Changes to public health measures in the last month include:

- On March 1, 2022, the province-wide vaccine proof policy was removed (which impacted restrictions on workplaces and public events). However, targeted restrictions remained in one First Nations community. As such, the stringency index did not change.
- On March 15, 2022, internal movement restrictions changed to recommendations. (SI 63 to 58)

As of March 18, 2022, current public health measures include:

- Schools: Targeted school closures remain in one First Nations community. Elsewhere in the province, schools are open with no mask or vaccination requirements.
- Workplaces: Targeted workplace closures remain in one First Nations community. Elsewhere in the province, masks are only required in some workplaces (*e.g.* healthcare settings), and there is no vaccine proof policy in effect.
- Public events: Targeted restrictions remain in one First Nations community.
- Gatherings: Targeted restrictions remain in one First Nations community. No restrictions elsewhere in the province.
- Stay-at-home orders: Targeted stay-at-home requirements remain in at least one First Nations community.

- Internal movement: Targeted recommendations not to travel to and from certain communities remain, although the province-wide order restricting travel for Northern Manitoba was lifted.
- International travel: isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: coordinated public information campaign remains (e.g. regular COVID-19 updates and briefings).

Ontario

Cases: Since peaking in early-January 2022, the weekly rolling average of cases has decreased. However, in recent weeks, case incidence has stabilized.

Deaths: Since peaking in late-January 2022, the weekly rolling average of deaths has decreased.

Vaccination: As of March 13, 2022, 48% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 50, as of March 18, 2022; this value has been in place since March 10, 2022. Changes to public health measures in the last month include:

- On February 27, 2022, one First Nations community in Ontario implemented school closures, workplace restrictions, and restrictions on gatherings in response to local COVID-19 activity. However, elsewhere in the province, restrictions on gatherings eased and the vaccine proof policy lifted on March 1, 2022, impacting restrictions on workplaces and public events. (SI 59 to 71)
- On March 10, 2022, restrictions eased in a First Nations community, which resulted in schools reopening, the easing of measures for workplaces and gatherings, and the lifting of stay-at-home requirements. (SI 71 to 50)
- On March 14, 2022, restrictions on gatherings further eased in the province; however, as restrictions remained stringent in a First Nations community the stringency index did not change.

As of March 18, 2022, current public health measures include:

- Schools: Mask mandates are in effect.
- Workplaces: Targeted workplace closures remain in one First Nations community. Elsewhere in the province, there is no vaccine proof policy in effect and workplaces are open with mask mandates in place.
- Public events: Targeted restrictions remain in one First Nations community. Elsewhere in the province, there are no vaccination requirements, but mask mandates remain in place.
- Gatherings: Targeted restrictions remain in one First Nations community.
- Internal movement: Targeted recommendations not to travel to and from certain communities remain.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

Quebec

Cases: Since peaking in early-January 2022, the weekly rolling average of cases has decreased. However, in recent weeks, case incidence has stabilized.

Deaths: Since peaking in late-January 2022, the weekly rolling average of deaths has decreased.

Vaccination: As of March 13, 2022, 49% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 38, as of March 18, 2022; this value has been in place since February 28, 2022. Changes to public health measures in the last month include:

- On February 28, 2022, targeted public health measures in one region as well as in the rest of the province of Quebec were lifted or eased, including, workplace restrictions, restrictions on public events, and restrictions on gatherings. (SI Index 54 to 38)

- On March 7, 2022, mask mandates lifted in school settings (with some exceptions). However, this did not change the stringency index.
- On March 12, 2022, Quebec's vaccine proof policy lifted for some venues, however, this did not change the stringency index, as some restrictions (*i.e.* mask mandates) remained in those venues.

As of March 18, 2022, current public health measures in place include:

- Schools: While there are no mask mandates for students, mask mandates are in effect for school staff and in specific situations.
- Workplaces: Workplaces open with mask mandates in effect. No vaccine proof policy in effect.
- Public events: Events permitted with mask mandates in effect for some. No vaccine proof policy in effect.
- Internal movement: Travel restrictions remain for Northern communities.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

Nova Scotia

Cases: Since peaking in early-January 2022, the weekly rolling average of cases has decreased. However, in the last two weeks, case incidence has increased.

Deaths: Since peaking in mid-February 2022, the weekly rolling average of deaths has decreased. However, fluctuations have been observed in the last two weeks.

Vaccination: As of March 13, 2022, 51% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 38, as of March 18, 2022; this value has been in place since February 28, 2022. Changes to public health measures in the last month include:

- Effective February 28, 2022, Nova Scotia's vaccine proof policy was lifted, which impacted restrictions on workplaces and public events. (Stringency Index 47 to 38)

As of March 18, 2022, current public health measures in place include:

- Schools: Mask mandates are in effect.
- Workplaces: Open with mask mandates in effect. No vaccine proof policy in effect.
- Public events: Events permitted with mask mandates in effect for some. No vaccine proof policy in effect.
- Gatherings: Capacity limits are in effect for indoor and outdoor gatherings.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

New Brunswick

Cases: Since peaking in early-January 2022, the weekly rolling average of cases has decreased. However, in the last two weeks, case incidence has fluctuated with an overall increasing trend.

Deaths: Since peaking in mid-February 2022, the weekly rolling average of deaths has decreased. However, an increase has been observed in the last two weeks.

Vaccination: As of March 13, 2022, 48% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 20, as of March 18, 2022; this value has been in place since March 14, 2022. Changes to public health measures in the last month include:

- On February 28, 2022, the vaccine proof policy was lifted, which impacted restrictions on workplaces and public events. (SI 42 to 38)
- On March 14, 2022, New Brunswick lifted many other restrictions, including those impacting workplaces, public events, and gatherings (as mask mandates lifted in most settings). (SI 38 to 20)

As of March 18, 2022, current public health measures in place include:

- Workplaces: Some workplaces (*e.g.* healthcare settings) require masks; mask mandates have been removed elsewhere, as has the vaccine proof policy.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

Newfoundland and Labrador

Cases: Since peaking in mid-January 2022, the weekly rolling average of cases has decreased. However, in the past month, case incidence has increased.

Deaths: Since peaking in mid-February 2022, the weekly rolling average of deaths has notably fluctuated.

Vaccination: As of March 13, 2022, 55% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 19, as of March 18, 2022; this value has been in place since March 14, 2022. Changes to public health measures in the last month include:

- As of February 28, 2022, schools reopened in a First Nations community in Newfoundland and Labrador, moving from targeted closures to recommended province-wide school measures. Additional province-wide changes also took effect on February 28, 2022, including the easing of restrictions on workplaces and public events. (Stringency Index 57 to 51)
- On Mar 14, 2022, the province lifted most remaining restrictions, impacting workplaces and public events as mask mandates were removed. As well, it was assumed that the outbreak in the aforementioned First Nations community ended, and that the community began to observe province-wide measures. (Stringency Index 51 to 19)

As of March 18, 2022, current public health measures in place include:

- Schools: Mask mandates are in effect.
- Workplaces: Some workplaces (*e.g.* healthcare settings) require masks; mask mandates have been removed elsewhere, as has the vaccine proof policy.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Public health officials are urging caution, but there are no longer regular updates and briefings.

Prince Edward Island

Cases: After peaking in late-January 2022, the weekly rolling average of cases decreased, then began increasing shortly after. Following another peak in early-March 2022, the weekly rolling average of cases has decreased.

Deaths: Since peaking in late-January 2022, the weekly rolling average of deaths has decreased.

Vaccination: As of March 13, 2022, 48% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 38, as of March 18, 2022; this value has been in place since February 28, 2022. Changes to public health measures in the last month include:

- On February 28, 2022, the vaccine proof policy was removed, which impacted restrictions on workplaces and public events. (SI 47 to 38)
- As of March 17, 2022, restrictions related to public events and gatherings eased. This, however, did not impact the stringency index.

As of March 18, 2022, current public health measures include:

- Schools: Mask mandates are in effect.
- Workplaces: Open with mask mandates in effect. No vaccine proof policy in effect.

- Public events: Events permitted with mask mandates in effect for some. No vaccine proof policy in effect.
- Gatherings: Capacity limits are in effect for indoor and outdoor gatherings.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

Yukon

Cases: Since peaking in mid-January 2022, the weekly rolling average of cases has decreased. However, in the last two weeks, cases have been observed to be fluctuating.

Deaths: Since peaking in early-February 2022, the weekly rolling average of deaths has decreased with some recent fluctuation observed.

Vaccination: As of March 13, 2022, 45% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 56, as of March 18, 2022. Changes to public health measures in the last month include:

- On March 4, 2022, territory-wide restrictions on gatherings eased, however, gathering limits remained in one community. (SI 60 to 59)
- On March 18, 2022, the vaccine proof policy (impacting workplaces and public events) as well as mask mandates. Targeted restrictions remain in one community. (SI 59 to 56)

As of March 18, 2022, current public health measures in place include:

- Schools: Mask mandates are in effect.
- Workplaces: Targeted workplace closures remain in one community. Elsewhere in the territory, there are no mask mandates and no vaccine proof policy in effect.
- Public events: Targeted restrictions remain in one community. Elsewhere in the territory, there are no mask mandates and no vaccine proof policy in effect.
- Gatherings: Targeted restrictions remain in one community. No restrictions elsewhere in the territory.
- Internal movement: Targeted travel restrictions to and from at least one community remains.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

Northwest Territories

Cases: Since peaking in early-February 2022, the weekly rolling average of cases has decreased.

Deaths: There have been extended periods with no COVID deaths. The weekly rolling average of deaths has fluctuated in recent weeks.

Vaccination: As of March 13, 2022, 40% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 46, as of March 18, 2022; this value has been in place since March 1, 2022. Changes to public health measures in the last month include:

- In the Northwest Territories, as of March 1, 2022, restrictions on gatherings lifted, as well as the vaccine proof policy, which impacted restrictions on workplaces and public events. (Stringency Index 57 to 46)

As of March 18, 2022, current public health measures in place include:

- Schools: Mask mandates are in effect.
- Workplaces: Targeted workplace closures remain in one community. Elsewhere in the territory, there is no vaccine proof policy in effect, but mask mandates remain.
- Public events: Targeted restrictions remain in one community. Elsewhere in the territory, there is no vaccine proof policy in effect, but mask mandates remain.

- Internal movement: Targeted travel restrictions to and from at least one community remain.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

Nunavut

Cases: After peaking in early-February 2022, the weekly rolling average of cases decreased, then began increasing shortly after. Following another peak in early-March 2022, the weekly rolling average of cases has decreased.

Deaths: There have been extended periods with no COVID deaths. There have been no deaths in the last two weeks.

Vaccination: As of March 13, 2022, 35% of the entire population is fully vaccinated with a booster dose.

Public Health Measures: The current stringency index is 42, as of March 18, 2022; this value has been in place since March 14, 2022. Changes to public health measures in the last month include:

- As of February 28, 2022, schools in two communities in Nunavut eased restrictions. This did not impact the territory's stringency index.
- On March 14, 2022, Nunavut eased workplace restrictions in some communities. (Stringency Index 44 to 42)

As of March 18, 2022, current public health measures in place include:

- Schools: Mask mandates are in effect.
- Workplaces: There is no vaccine proof policy, but mask mandates are in effect. As well, some communities have more stringent capacity restrictions than others.
- Public events: There is no vaccine proof policy, but mask mandates are in effect. As well, some communities have more stringent capacity restrictions than others.
- Gatherings: Capacity limits remain territory-wide; some communities have more stringent limits than others.
- Internal movement: Recommendations not to travel between communities remain.
- International travel: Isolation and testing requirements remain for unvaccinated travelers.
- Public information campaigns: Coordinated public information campaign remains.

Table 2. Provinces and territories; weekly rolling average of daily cases and deaths of COVID-19/100,000, test positivity, vaccination coverage and information on containment and health interventions (as of March 18, 2022 unless otherwise indicated).

Province or territory	Weekly rolling average of daily cases/100,000*	Weekly rolling average of percent (%) test positivity	Weekly rolling average of daily deaths/100,000	Percent (%) of entire population fully vaccinated + additional dose (as of Mar 13)	Stringency index
British Columbia	4.2 (↓)	5.9%	0.09	48%	42
Alberta	11.3 (↑)	20.3%	0.12	36%	20
Saskatchewan	10.1 (↓; Mar 12)	13.4%	0.27 (Mar 12)	41%	17
Manitoba	12.9 (stable)	14.8%	0.17	42%	58
Ontario	12.4 (stable)	12.3%	0.06	48%	50
Quebec	12.7 (stable)	10.3%	0.15	49%	38
Nova Scotia	41.6 (↑; Mar 15)	25.5%	0.20 (Mar 15)	51%	38
New Brunswick	36.3 (↓; Mar 15)	28.4%	0.14 (Mar 15)	48%	20
Newfoundland and Labrador	110.3 (↑)	34.4%	0.25	55%	19
Prince Edward Island	208.8 (↓; Mar 16)	8.7%	0 (Mar 16)	48%	38
Yukon	24.3 (stable)	NA	0	45%	56
Northwest Territories	103.3 (↓)	27.3%	0	40%	46
Nunavut	58.4 (↓; Mar 15)	12.5%	0 (Mar 15)	35%	42

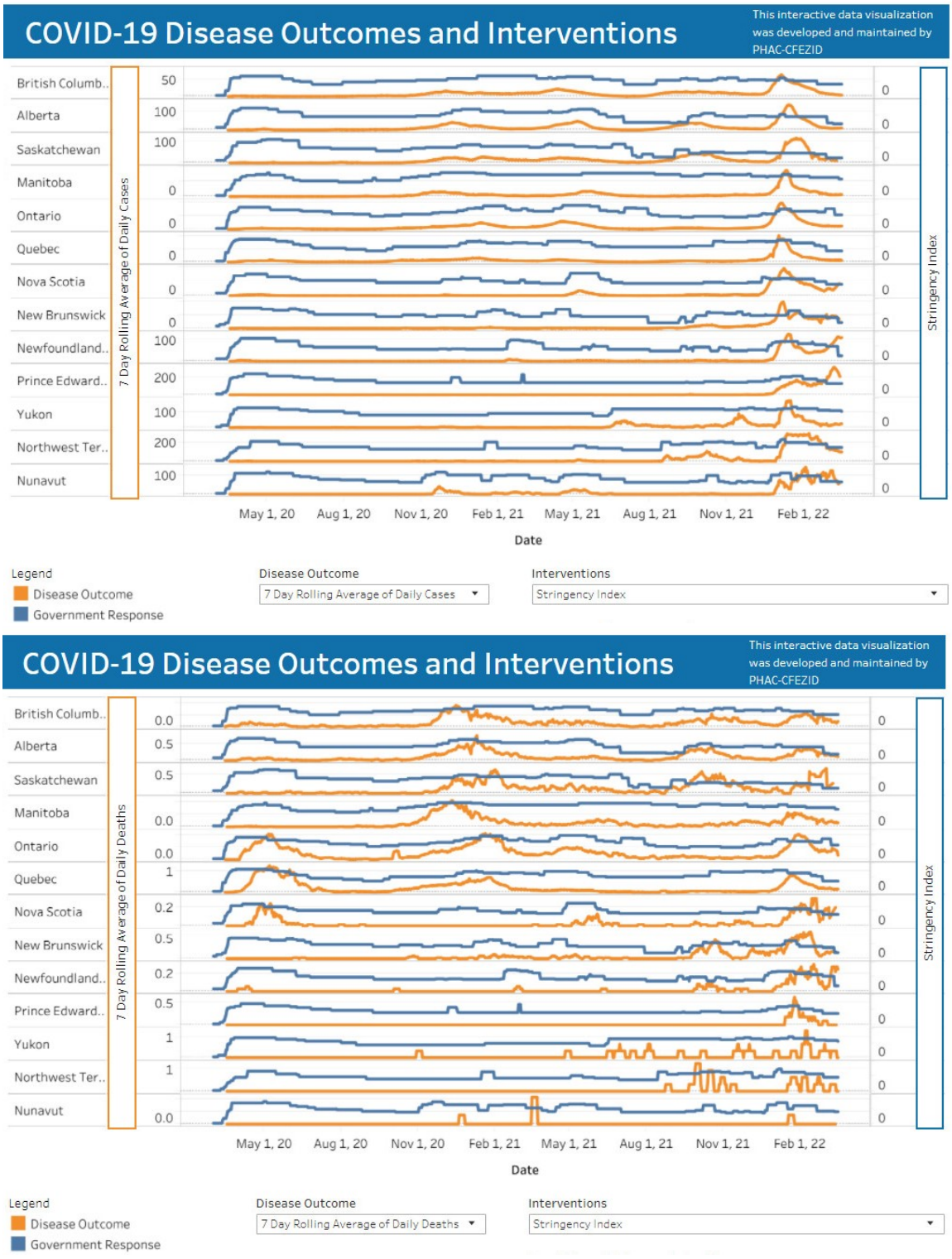
*Weekly change is how the current week (days 1 to 7 days ago) compares against the previous week (8 to 14 days ago). ↓ = 10-100% decrease; Stable < 10% increase or decrease; ↑ = 10-100% increase; NA = Data unavailable (as per the March 21, 2022 Trend Report; these numbers may differ from those produced on other dates).

Data source: Data on cases and deaths are from provincial and territorial websites (as per the Trend Report produced on March 21, 2022). Data on test positivity is from the National Microbiology Laboratory (NML). Data for laboratory analyses, standardized to the July 1, 2021, post-census population estimate. Data on booster dose coverage from the Government of Canada's Health InfoBase. Accessed on: 2022-03-22. Available at: https://health-infobase.canada.ca/covid-19/vaccination-coverage/.

References

1. The Centre for Health Protection (CHP) of the Department of Health. Hong Kong: Department of Health, March 23, 2022. Available from: https://www.chp.gov.hk/files/pdf/local_situation_covid19_en.pdf

Figure 2. Provincial/territorial weekly rolling average of daily cases (top) and deaths (bottom) of COVID-19/100,000 population and information on containment and health interventions (current as of March 18, 2022).



Data source: Data on cases and deaths from provincial and territorial websites. Stringency index data are primarily from data mining and coding of publicly available information by the Public Health Agency of Canada.

4 DYNAMIC MODELLING

4.1 AGENT-BASED MODEL: EXPLORING THE IMPACT OF BOOSTER ADMINISTRATION SCENARIOS, AND WANING IMMUNITY, ON SARS-COV-2 TRANSMISSION FOLLOWING THE OMICRON WAVE

Key Points

- Simulations suggest that, despite relatively low booster uptake, due to the high level of post-infection and post vaccination immunity in the Canadian population, the current lifting of public health measures is not anticipated to cause a resurgence in the number of hospitalizations that would exceed previous waves.
- Overall, comparing different scenarios for booster uptake, as well as speed and timing of booster rollout, there were only small differences in the number of cases, hospitalisations and deaths.
- Delaying increased uptake of boosters until early fall had the greatest impact on reducing a wave in fall-winter 2022-2023.
- Simulations assume that a new variant of concern does not invade and become established in Canada.

Note: Supplemental information on methods and/or results for this report is provided in Annex 5.2.4.

Background

As the Omicron wave in Canada subsides, many jurisdictions are lifting almost all public health measures simultaneously. The PHAC agent-based model (ABM) has been updated to the changing situation in Canada and has been adapted to model waning immunity specific to each variant with updated data [1, 2].

This report explores the impact of deploying boosters at the current administration rate and at an expedited rate on Omicron reinfections and hospitalisations in the coming months. Two levels of booster acceptance were explored; 55% of the eligible population (18 years and older) which represents the current situation in Canada and 88% of the eligible population, corresponding to a 100% acceptance rate of boosters for those who have already received their second dose. Additionally, the impact of delaying booster administration to fall 2022 for those who have not already received their booster was explored.

Methods

Detailed methods on the ABM have been previously published [3-5]. Further details are in the Annex 5.2.4.

Vaccination rollout

The vaccination rollout in the model was implemented according to observed vaccine uptake in the population provided by the Canadian Immunization Committee (CIC) [6], and the rollout of vaccines follows the order of priority groups as recommended by the National Advisory Committee on Immunization (NACI) (Figure A.3, Annex 5.2.4) [7]. First dose, second dose and third dose (booster) vaccination rates are modelled on the past and current rollout and projected into the future months based on the most recent vaccination rates except where specified [8].

In the model, individuals are selected for vaccination if they are (i) 5 years and over, (ii) not presenting symptoms of infection (but when individuals recover from an infection, they become available for vaccination) and (iii) willing to be vaccinated according to an age-specific vaccine acceptance level (Table 1). Willingness to vaccinate for children (5 to 11 age group) and adolescents (12 to 17 age group) is dependent on vaccine acceptance in households, i.e. probability of being vaccinated is applied only if at least one adult in the household is willing to vaccinate. Parents of children have a slightly reduced willingness to accept vaccination for their children compared to parents of adolescents, based on survey and empirical data [6, 9] (Table 1). Vaccine acceptance data are from the CIC March 17, 2022 report with data up to and including March 13, 2022 [6]. An additional 1% to 2% of vaccine acceptance of the first dose is projected for the 12 to 59 age group while an additional 8% is projected for the 5 to 11 age group; representing the respective anticipated uptake in the model based on actual vaccine uptake in recent weeks [6]. Vaccine acceptance for the second dose is modelled as a proportion of those who have received their first dose, the actual second dose coverage given first dose is modelled except in the 5 to 11 age group due to ongoing second dose administration in this group. Second dose acceptance in 5 to 11 age group is modelled on 12 to 17 age group acceptance (Table 1) [6].

Table 1. Age-specific modelled and actual vaccine acceptance of the first and second doses.

Age group	Actual first dose acceptance [6]	Modelled first dose acceptance	Actual second dose acceptance in those with a first dose [6]	Modelled second dose acceptance in those with a first dose
5 to 11 (children)	57%*	65%	65%*	95%
12 to 17 (adolescents)	88%	90%	96%	96%
18 to 29	90%	90%	96%	96%
30 to 39	89%	90%	97%	97%
40 to 49	91%	92%	98%	98%
50 to 59	91%	92%	98%	98%
60 to 69	95%	95%	98%	99%
70 to 79	98%	98%	99%	99%
80 and over	99%	99%	98%	99%

* First and second dose vaccination in the 5 to 11 years age group is ongoing as of March 13, 2022; the acceptance values are therefore modelled higher than actual values compared to the other age groups.

The overall modelled willingness to receive two doses is 82% of the total population and 86.5% of the eligible population 5 years and over. Vaccination begins on December 14, 2020. Individuals in the model vaccinated prior to March 4, 2021 receive a second dose of the vaccine 28 days after the first dose, while individuals vaccinated on or after March 4, 2021 receive a second dose with a delayed dose interval of four months, as recommended by NACI [8, 10]. Individuals in the 5 to 11 age group are vaccinated with a 56-day (8-week) dose interval as recommended by NACI [11]. The vaccination rate for the 5 to 11 age group is 158 doses per day per 100,000 people

in the first week of December 2021 reflecting real-life vaccination rate for this age group [8]. Based on the most recent weeks of available data, children vaccination has declined and is modelled to decline gradually to 1 per day per 100,000 by April 2022 [6]. Vaccination of the 5 to 11 age group commences on November 19, 2021 (dose 1) and ends approximately at the end of June, 2022 (dose 2) based on the estimated target rates.

A one-time booster dose is administered in the model starting on September 17, 2021 to individuals aged 18 years and over, after a minimum of three months following the receipt of the second dose, based on NACI recommendation [12]. Boosters are administered following the same order of prioritization as the administration of the first and second doses, which in the general population, is ordered from the eldest to the youngest. Similar to the second dose, the booster dose is modelled as a proportion of those who have received their second dose (Table 2). With the actual booster dose coverage given second dose, the overall booster acceptance is 55% for the adult population. When the modelled third dose acceptance given second dose is increased to 100%, the overall booster acceptance for the adult population becomes 88% (i.e. 88% of the eligible population 18+ is projected to receive the second dose, see Table 5). Further details on the vaccination rollout are included in the Annex (see Vaccination sub-section).

Table 2. Age-specific modelled and actual vaccine acceptance of the third (booster) dose.

Age group	Actual third dose acceptance given second dose [4]	Modelled third dose acceptance given second dose (55% boosted scenario)	Modelled third dose acceptance given second dose (88% boosted scenarios including 55% current rate, 33% delay scenario)
5 to 11 (children)	0.02%	N/A	N/A
12 to 17 (adolescents)	15%	N/A	N/A
18 to 29	39%	39%	100%
30 to 39	48%	48%	100%
40 to 49	57%	57%	100%
50 to 59	68%	68%	100%
60 to 69	80%	80%	100%
70 to 79	86%	86%	100%
80 and over	87%	87%	100%

Protection acquired from natural infection and vaccination

It is assumed that infection provides the same level of protection afforded by two doses of the vaccine (Table 3). Maximal vaccine effectiveness (VE) against infection, clinical symptoms and severe health outcomes increases from dose 1 to dose 2 for the wild-type strain (WT) and variants (Table 3). For the WT, Alpha and Delta variants, a third-dose booster is assumed to boost waning protection against infection, clinical symptoms and hospitalisations up to the same level acquired by two doses. For the Omicron variant, the protection acquired from the booster against infection and symptoms is higher relative to the protection acquired from two doses, but due to greater immune escape of this variation, protection acquired from boosters against Omicron infections, symptoms and hospitalisations is lower compared to protection against WT and the other variants (Table 3). The receipt of the booster during the waning immunity period increases protection to the maximum VE afforded by the booster for each corresponding strain and provides three additional months in which immunity is retained before waning begins (see *Waning immunity* section). A previous infection with a specific variant is assumed to lead to a 99%, 99.5%, 99.9% and 99.9% maximal protection against reinfection, symptoms, hospitalisation and death, respectively,

from that same variant prior to waning. Further details on VE against infection, clinical symptoms, hospitalisations and deaths can be found in the Annex 5.2.4 (see *Vaccination* section).

Waning immunity

It is assumed that waning immunity commences after a 90-day period following full recovery from infection or following a second or a booster dose with immunity waning linearly over time (Table 3). Waning is assumed to decrease infection-acquired and vaccine-acquired protection against SARS-CoV-2 infection, symptoms and hospitalisation but protection against death persists. A linear decrease of protection over time is applied on the population-level VE estimates (with conditional VE estimates recalculated each day based on the linear decrease). Compared to previous modelling reports, the ABM has been updated and immunity now wanes at a rate specific to each variant and each outcome (i.e. infection, symptoms and hospitalisations) [1, 2]. Immunity wanes from a maximal protection level down to a minimal protection level over a given time period after a 90-day time-to-waning period (Table 3), after which the protection is retained at the minimal protection level indefinitely. The rate of decline is assumed to be constant across age groups. Further assumptions on waning immunity are presented in the Annex (see *Model baseline* section).

Variants of concern (VOC)

The model assumes the emergence of a first VOC on December 1, 2020, introduced by imported cases entering the population with a 10% probability that an imported case enters with a VOC, up to a 100% probability by August 29, 2021 (Annex 5.2.4, Figure A-5). This first VOC is modelled on the Alpha variant, which is 50% more transmissible and 40% more virulent than the wild-type strain (WT) but does not demonstrate immune escape characteristics (Table 4) [13-15].

On March 9, 2021, imported cases entering with a VOC could be either Alpha or Delta variant. The number of Delta introductions is inversely proportional to Alpha introductions and reflects the global situation as Delta dominates over time. Delta is introduced with a 1.6% probability of all VOCs on March 9, 2021 and increases linearly over time to complete dominance (100%) by August 29, 2021. It is assumed that Delta is 100% more transmissible and 80% more virulent than WT [13-15]. Last, Delta is assumed to partially evade protection afforded by mRNA vaccines and protection from previous infections with other variants. This immune escape is modelled as a 33% reduction in the protection against infection following the first dose (before receiving the second dose) and 6% reduction following the second dose and the booster [13-15]. It is assumed that immunity from vaccine or previous infections continues to provide strong protection against severe disease caused by Delta [13-15]. (Table 4).

On November 20, 2021, imported cases entering with a VOC could be either Delta variant or Omicron (B.1.1.529) variant. The proportion of imported VOCs that are Omicron increases linearly over time from 10% to complete dominance (100%) by December 31, 2021. It is assumed that Omicron is 250% more transmissible than the wild-type (i.e. 175% more transmissible than Delta) and 30% less virulent than the wild-type [16]. The Omicron variant is assumed to partially evade protection afforded by mRNA vaccines and protection from previous infections with other variants, with a reduction in protection against infection, symptoms and hospitalisations (see Table 4) [17, 18].

Immune escape characteristics are assumed to be the same across all age groups. The rate of COVID-19 cases entering the ABM population have been updated to reflect the latest estimates from the PHAC importation risk model, involving a large number of imported cases during the months of January and February 2022 due to increasing global transmission of Omicron (see Annex 5.2.4).

Table 3. Assumptions on population-level protections following administration of dose 1, 2 and a booster or following natural infection, and on the time to and duration of waning immunity.

Variant	Dose	Protection against	Population-level protection		
			Maximal protection	Minimal protection	(Time-to-waning period) + duration of waning period
Wild-type and Alpha	Dose 1	infection	60%	N/A – no waning after dose 1	
		symptoms	66%		
		hospitalisation	80%		
		death	85%		
	Dose 2, booster and natural infection	infection	92%	0%	(90) + 1,434 days
		symptoms	94%	0%	(90) + 1,434 days
		hospitalisation	96%	0%	(90) + 6,321 days
		death	96%	N/A	N/A
Delta	Dose 1	infection	40%*	N/A – no waning after dose 1	
		symptoms	66%		
		hospitalisation	80%		
		death	85%		
	Dose 2, booster and natural infection	infection	86%*	0%	(90) + 1,434 days
		symptoms	94%	0%	(90) + 1,434 days
		hospitalisation	96%	0%	(90) + 6,321 days
		death	96%	N/A	N/A
Omicron	Dose 1	infection	20%*	N/A – no waning after dose 1	
		symptoms	25%*		
		hospitalisation	58%*		
		death	85%		
	Dose 2 and natural infection	infection	45%*	5%	(90) + 220 days
		symptoms	60%*	5%	(90) + 220 days
		hospitalisation	86%*	5%	(90) + 5,443 days
		death	96%	N/A	N/A
	Booster	infection	70%*	5%	(90) + 220 days
		symptoms	72%*	5%	(90) + 220 days
		hospitalisation	86%*	5%	(90) + 5,443 days
		death	96%	N/A	N/A
Same variant reinfection protection, i.e. alpha against alpha reinfection		infection	99%	0% (alpha/delta), 5% (Omicron)	(90) + 1,434 days (alpha/delta), (90) + 220 days (Omicron)
		symptoms	99.5%	0% (alpha/delta), 5% (Omicron)	(90) + 1,434 days (alpha/delta), (90) + 220 days (Omicron)
		hospitalisation	99.9%	0% (alpha/delta), 5% (Omicron)	(90) + 6,321 days (alpha/delta), (90) + 5,443 days (Omicron)
		death	99.9%	N/A	N/A

*The variants Delta and Omicron are associated with lower maximal protection due to their immune escape characteristics (see Variants of concern (VOC) section below)

Table 4. Characteristics for variants of concern as modelled in the ABM.

Characteristics		Variants of Concern		
		Alpha (B.1.1.7)	**Delta (B.1.617.2)**	**Omicron (B.1.1.529)**
Transmissibility compared to WT strain		50% increase	100% increase	250% increase
Virulence compared to WT strain		40% increase	80% increase	30% reduction
Immune escape compared to wild-type strain (see Table 3)	Protection against infection	No reduction Dose 1: 60%, same as WT protection Dose 2/natural infection: 92%, same as WT protection Booster: 92%, same as WT protection	Dose 1: 33% reduction on the 60% WT protection Dose 2/natural infection: 6% reduction on the 92% WT protection Booster: 6% reduction on the 92% WT protection	Dose 1: 67% reduction on the 60% WT protection Dose 2/natural infection: 51% reduction on the 92% WT protection Booster: 24% reduction on the 92% WT protection
	Protection against symptoms	No reduction Dose 1: 66%, same as WT protection Dose 2/natural infection: 94%, same as WT protection Booster: 94%, same as WT protection	No reduction Dose 1: 66%, same as WT protection Dose 2/natural infection: 94%, same as WT protection Booster: 94%, same as WT protection	Dose 1: 63% reduction on the 66% WT protection Dose 2/natural infection: 36% reduction on the 94% WT protection Booster: 23% reduction on the 94% WT protection
	Protection against hospitalisations	No reduction Dose 1: 80%, same as WT protection Dose 2/natural infection: 96%, same as WT protection Booster: 96%, same as WT protection	No reduction Dose 1: 80%, same as WT protection Dose 2/natural infection: 96%, same as WT protection Booster: 96%, same as WT protection	Dose 1: 27% reduction on the 80% WT protection Dose 2/natural infection: 10% reduction on the 96% WT protection Booster: 10% reduction on the 96% WT protection
	Protection against death	No reduction	No reduction	No reduction

Model scenarios

All scenarios were modelled on a baseline calibrated to hospital prevalence (i.e. total patients in hospital) in Canada. All scenarios included the vaccinations of children (5 to 11 years) and the administration of boosters to individuals 18 years and older (see *Vaccination* section).

Four scenarios were explored with varying assumptions on booster administration:

1. 55% boosted, current rate: 55% of the eligible population (18+) is willing to receive the booster. This represents 63% of the adult population who have received two doses and is the current situation in Canada [6]. The rate of booster administration is based on the current booster rollout (commencing at 26 doses per day per 100,000 people in September 2021 to 861 doses per day per 100,000 people in the second week of January, then 43 doses per day on the week of March 12 to March 18, 2022). A booster rate of 225 doses per day is applied moving forward for the remainder of the booster administration period.
2. 88% boosted, current rate: 88% of the eligible population (18+) is willing to receive the booster. This represents 100% of adults who have received two doses. The booster rate is the same as in scenario 1.
3. 88% boosted, expedited rate: 88% of the eligible population (18+) is willing to receive the booster (i.e. 100% of adults who have received two doses). The rate of booster administration is substantially increased on March 19, 2022 to a rate comparable to the peak of administration in summer 2021 (1,392 doses per day per 100,000 people). This booster rate is applied moving forward for the remainder of the booster administration period.
4. 55% boosted, current rate, 33% delayed: 55% of the eligible population (18+) is willing to receive the booster (i.e. 63% of adults who have received two doses), applying the same booster rate as in the scenario 1. In fall 2022, the remaining adults who have only received two doses by then (i.e. 33% of the 18+ eligible population who have not yet received their booster dose) are now willing to receive the booster commencing September 1, 2022. The booster rate applied during this fall booster administration period is 250 doses per day per 100,000 people (equal to the mean of the daily rates during the winter-spring booster administration period).

Booster administration in these scenarios coincided with the gradual lifting of public health measures that were implemented during the Omicron wave. Shutdowns, increasing physical distancing and compliance to physical distancing, and an extension of the vaccine mandate were implemented on January 3, 2022. The de-escalation of these public health measures were applied in the following manner:

- Schools were reopened to 100% on February 14, 2022;
- A gradual reopening to 100% of non-essential businesses from February 14 to March 14, 2022;
- A gradual reopening to 80% of workplaces from February 14 to March 14, 2022 (representing a proportion of the workforce who will continue to telework);
- A gradual return to 80% pre-COVID contact rates by March 14, 2022;
- The elimination of a vaccine mandate on March 1, 2022;
- No reintroduction of these public health measures for the remaining model time period;
- Minimal case detection and isolation continues to be in place (20% of cases are detected and adheres to isolation)*;
- Minimal contact tracing and quarantine continues to be in place (50% of the detected cases are successfully traced and adheres to quarantine)*.

* While in reality test and trace activities have reduced, it is assumed the self-testing has a similar effect on transmission as these modelled public health interventions

Key model output metrics from simulations are extracted for the time period corresponding to the end of the first Omicron wave (April 1, 2022) to the model run end (January 1, 2024).

Results

Key model output metrics are presented in Table 5. Daily clinical infections, asymptomatic infections and hospital prevalence are presented in Figures 1 to 3.

In the updated model, it is assumed that approximately 55% of the total population has been previously infected with at least one SARS-CoV-02 infection by April 1, 2022; the majority of these are Omicron infections. Under this assumption, in all scenarios explored, the simultaneous lifting of public health measures in February and March of 2022 did not cause a resurgence that would exceed the number of cases, hospitalisations and deaths observed during the Omicron wave in winter 2022 (Figures 1 to 3; deaths not presented). Projected hospitalisations were estimated to be below the hospital bed capacity threshold (Figure 3).

The modelled waning immunity simulations suggest that regular resurgences will occur between April 1, 2022 and January 1, 2024. Resurgences will be characterized by a high number of Omicron reinfections with progressively increasing clinical and asymptomatic infections following each subsequent resurgence due to increasing immunity from infection in the population. Although hospitalisations also occurred during the resurgences, hospitalisations remained relatively stable and low in numbers compared to the Omicron wave. This was due to the assumption that protection against hospitalisation wanes slower over time than protection against infection (5,443 days, or approximately 15 years to complete loss of immunity compared to 220 days for protection against reinfection), thus preventing hospitalisations from reaching the levels observed during the first Omicron wave. However, these projections assume no new variant will emerge in the coming months and years which could have a very different impact on reinfections and hospitalisations.

Amongst the four scenarios for booster uptake and administration, there were only small differences in cases, hospitalisations and deaths over the whole post-Omicron period of the simulations (Table 4). Increasing boosters (88% boosted scenarios) would reduce a spring 2022 resurgence by a small amount and which did not significantly impact hospitalisations (Figures 1 to 3). Delaying the remaining booster administration to fall 2022 resulted in a slightly higher resurgence in spring 2022 but a lower resurgence in fall-winter 2022-2023.

These scenarios do not explore the impact of an annual booster which would likely reduce subsequent resurgences. This analysis also did not explore the emergence of a new variant, and impacts of boosters will depend on the characteristics of the new variant and the booster vaccines.

Conclusion

The simulation here suggests that, as a large proportion of the Canadian population has post-infection and/or post-vaccination immunity against SARS-CoV-2 infection, the lifting of public health measures will not cause a resurgence in the number of cases, hospitalisations and deaths that exceeds those observed during the Omicron wave. Despite waning immunity and a significant reduction in booster uptake compared to the second dose, the protection acquired from a milder variant and a two-dose vaccine by the majority of the Canadian population will likely provide

sufficient long-lasting protection against hospitalisation and death arising from frequent reinfections. Increasing booster uptake and expediting the current booster rollout did not substantially reduce cases, hospitalisations and deaths with the exception of increasing booster uptake in fall 2022 that somewhat reduced the fall-winter 2022-2023 wave.

Table 5. Key model output metrics extracted for the time period corresponding to the end of the first Omicron wave (April 1, 2022) to the model run end (January 1, 2024). Metrics are presented as the median value (with 95% credible intervals) summarizing 50 model realizations for each scenario.

Projected numbers from April 1, 2022 to January 1, 2024	55% boosted, current rate	88% boosted, current rate	88% boosted, expedited rate	55% boosted, current rate, 33% delayed
Total cases per 100,000*	312.3 (292.7-331.5)	318.1 (309.4-326.2)	313.4 (305.5-321.5)	295.3 (286.4-305)
Clinical cases per 100,000	50.3 (46.9-53.7)	51.6 (50-54.7)	50.9 (48.2-53.9)	48.6 (46-51.3)
Asymptomatic cases per 100,000*	261.8 (245.8-277.9)	266.9 (258.5-272.8)	262.1 (255.7-268.8)	247.1 (239.5-256.5)
Acute hospitalisations per 100,000	0.9 (0.8-1.1)	0.9 (0.8-1.2)	0.9 (0.8-1.1)	1 (0.8-1.2)
ICU admissions per 100,000	0.3 (0.2-0.3)	0.3 (0.2-0.3)	0.3 (0.2-0.3)	0.3 (0.2-0.4)
Deaths per 100,000	0.1 (0.1-0.2)	0.1 (0.1-0.2)	0.1 (0.1-0.2)	0.1 (0.1-0.2)
Proportion vaccinated dose 2 - total population	82 (81.8-82.2)	82 (81.7-82.1)	82 (81.8-82.2)	82 (81.8-82.2)
Proportion vaccinated dose 2 - eligible population (5+)	86.5 (86.3-86.6)	86.4 (86.2-86.6)	86.5 (86.3-86.6)	86.4 (86.3-86.7)
Proportion vaccinated dose 2 - adult population (18+)	88.5 (88.3-88.7)	88.5 (88.3-88.7)	88.5 (88.4-88.8)	88.5 (88.4-88.7)
Proportion boosted in winter-spring - eligible population (18+)	55.4 (55.1-55.7)	88.5 (88.3-88.7)	88.5 (88.4-88.8)	55.4 (55-55.7)
Proportion boosted in fall - eligible population (18+)	0 (0-0)	0 (0-0)	0 (0-0)	33.2 (32.9-33.4)
Booster vaccination end day	March 10, 2022	July 21, 2022	April 21, 2022	January 3, 2023

*The total and asymptomatic cases are higher than the model population (100,000) due to the prolong model run period and persistent reinfections in the population. They do not capture unique infections in the population.

Figure 1. Projected epidemic curves showing a) the daily clinical incidence per 100,000 people and b) the daily booster administrations per 100,000 people for four scenarios. The grey line and grey shaded area represents the smoothed median and 95% credible intervals, respectively, from 50 model realizations per scenario. The solid blue bar represents the booster administration period which begins on September 17, 2021 in each scenario and ends on various dates (see Table 4). The vertical blue solid line represents the date when public health measures, closures and physical distancing begins to be gradually lifted (February 14, 2022).

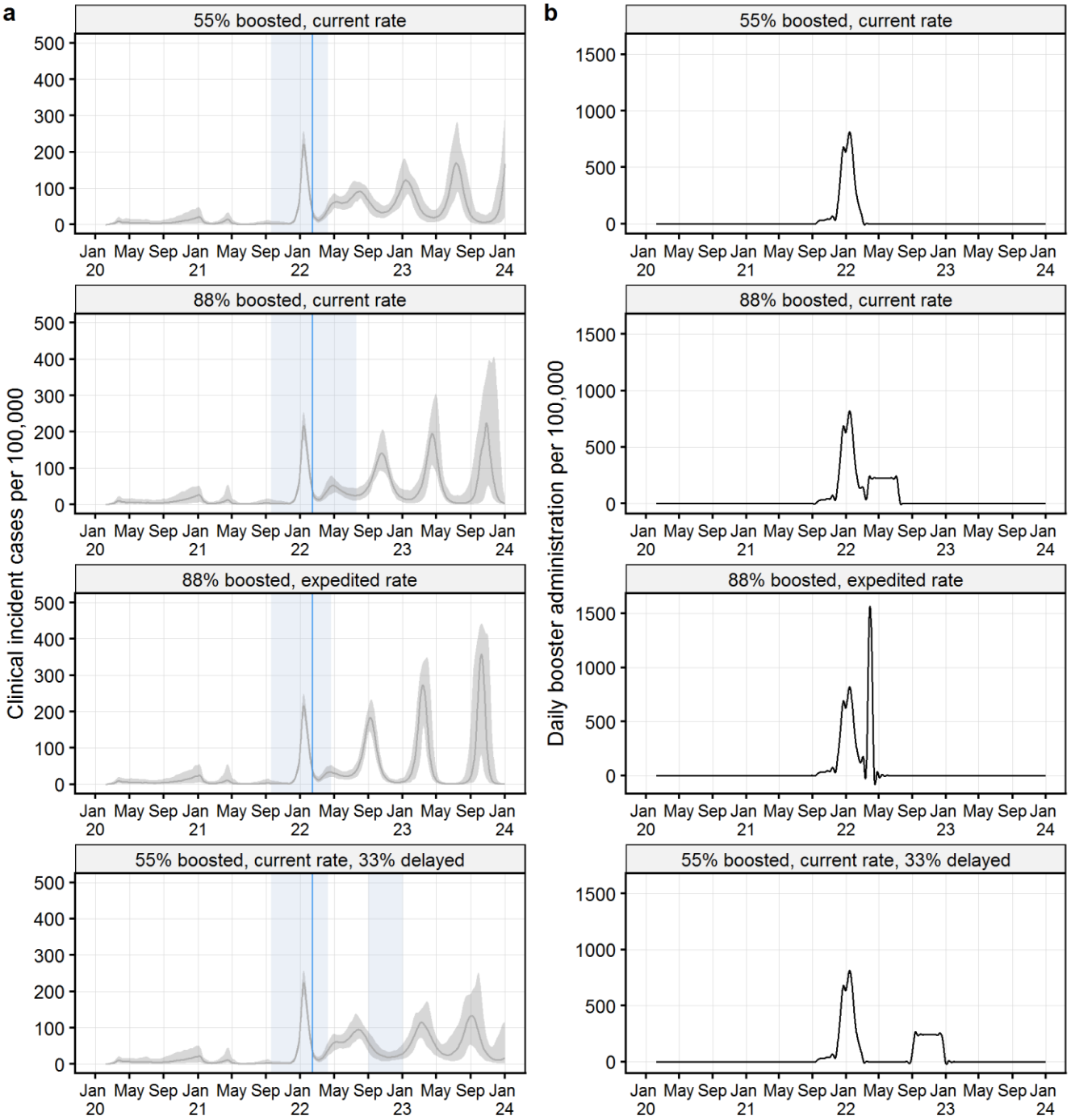


Figure 2. Projected epidemic curves showing a) the daily asymptomatic incidence per 100,000 people and b) the daily booster administrations per 100,000 people for four scenarios. The grey line and grey shaded area represents the smoothed median and 95% credible intervals, respectively, from 50 model realizations per scenario. The solid blue bar represents the booster administration period which begins on September 17, 2021 in each scenario and ends on various dates (see Table 4). The vertical blue solid line represents the date when public health measures, closures and physical distancing begins to be gradually lifted (February 14, 2022).

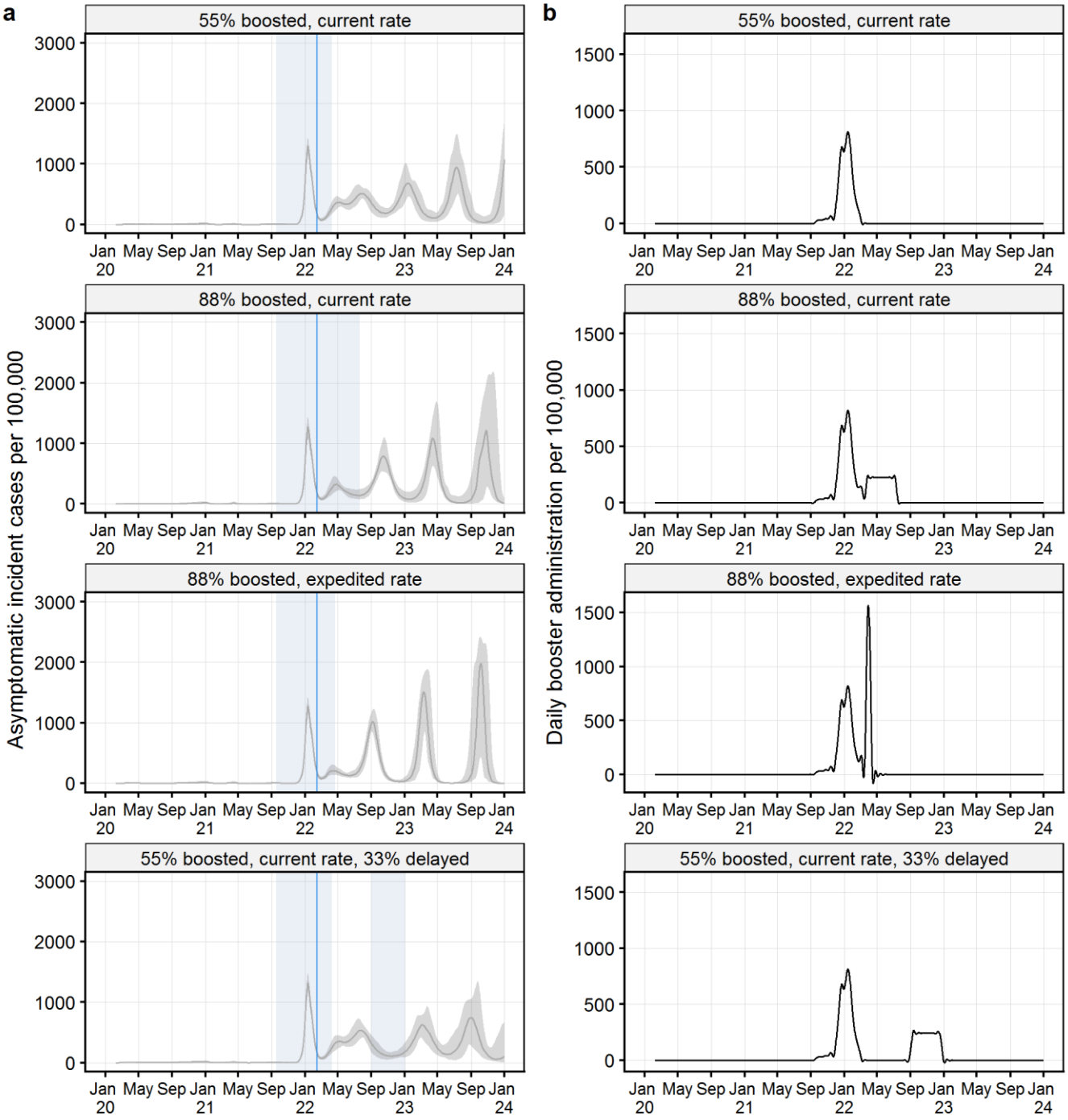
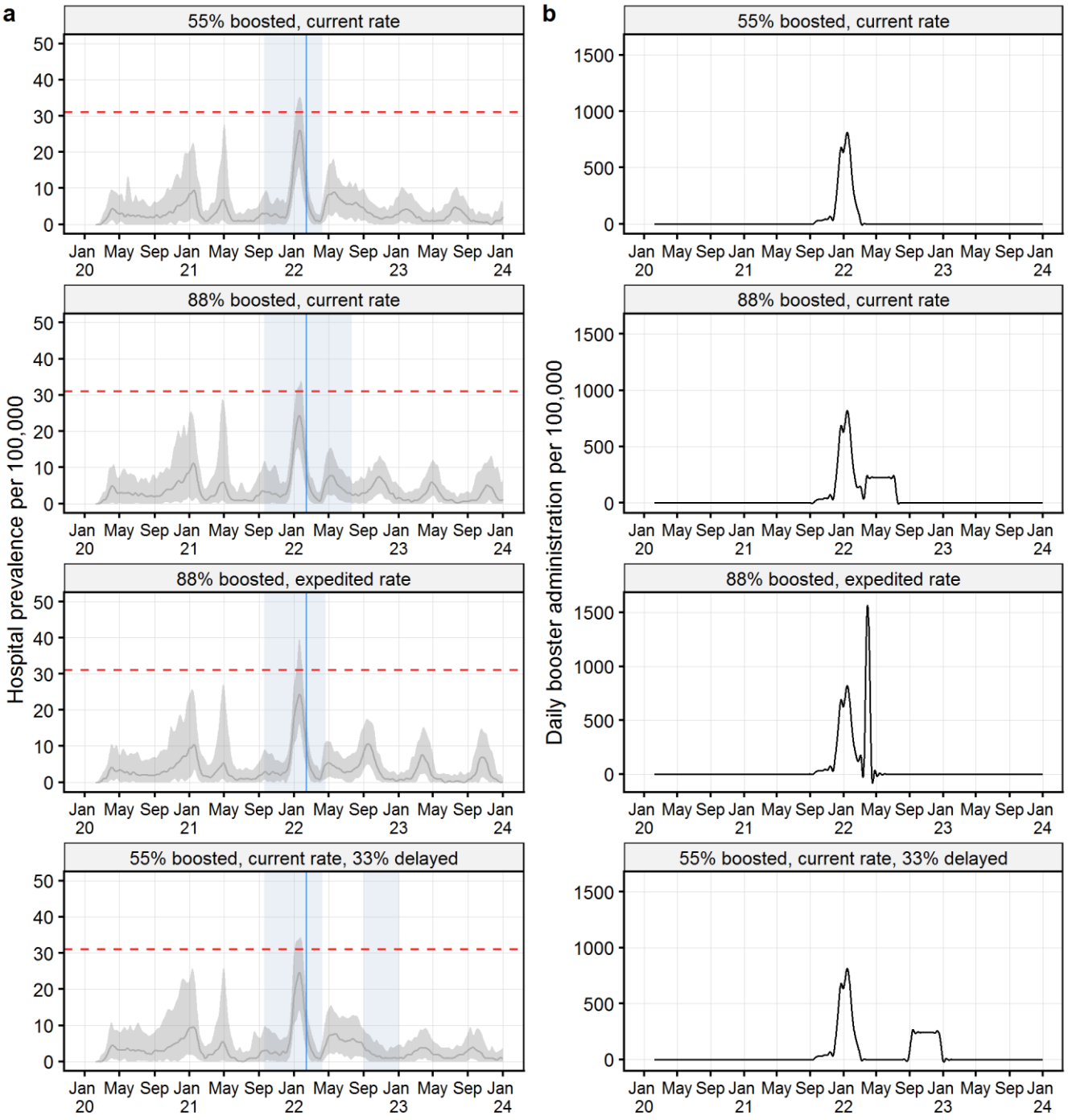


Figure 3. Projected epidemic curves showing a) the daily hospital prevalence per 100,000 people and b) the daily booster administrations per 100,000 people for four scenarios. The black line and grey shaded area represents the smoothed median and 95% credible intervals, respectively, from 50 model realizations per scenario. The solid blue bar represents the booster administration period which begins on September 17, 2021 in each scenario and ends on various dates (see Table 4). The vertical blue solid line represents the date when public health measures, closures and physical distancing begins to be gradually lifted (February 14, 2022). The red dashed horizontal line represents the number of Canadian hospital beds available for COVID-19 patients (31 hospital beds per 100,000; updated January 25, 2021 from Health Canada data, not that this number varies by P/T).



References

1. Buchan, S.A., et al., *Effectiveness of COVID-19 vaccines against Omicron or Delta symptomatic infection and severe outcomes.* medRxiv, 2022.
2. UK Health Security Agency, *COVID-19 vaccine surveillance report, Week 4, 27 January 2022*. 2022.
3. Ng, V., et al., *Projected effects of nonpharmaceutical public health interventions to prevent resurgence of SARS-CoV-2 transmission in Canada.* Canadian Medical Association Journal, 2020. **192**(37): p. E1053.
4. Ng, V., et al., *Modelling the impact of shutdowns on resurging SARS-CoV-2 transmission in Canada.* Royal Society Open Science, 2021. **8**(5): p. 210233.
5. Gabriele-Rivet V, et al., *Modelling the impact of age-stratified public health measures on SARS-CoV-2 transmission in Canada. .* Royal Society Open Science, 2021. **8: 210834**.
6. Canadian Immunization Committee (CIC), *COVID-19 vaccination coverage in Canada. Weekly report to the Canadian Immunization Committee (CIC), March 17, 2022 report. Data also available at https://health-infobase.canada.ca/covid-19/vaccination-coverage/*. 2022.
7. Government of Canada. *Guidance on the prioritization of initial doses of COVID-19 vaccine(s)*. 2021; Available from: *https://www.canada.ca/en/public-health/services/immunization/national-advisory-committee-on-immunization-naci/guidance-prioritization-initial-doses-covid-19-vaccines.html*.
8. COVID-19 Tracker Canada. *COVID-19 Vaccination Tracker*. 2022 [cited 2022 January 8, 2022]; Available from: *https://covid19tracker.ca/vaccinationtracker.html*.
9. MacDonald SE, Gagneur A, and COVImm study team, *Parents' COVID-19 vaccination intentions for children: COVImm national survey preliminary results, collected Dec 10-24 2020. Unpublished report from the Applied immunization (Aimm) research program*. 2021.
10. Government of Canada. *NACI rapid response: Extended dose intervals for COVID-19 vaccines to optimize early vaccine rollout and population protection in Canada*. 2021 [cited 2021 March 4, 2021]; Available from: *https://www.canada.ca/en/public-health/services/immunization/national-advisory-committee-on-immunization-naci/rapid-response-extended-dose-intervals-covid-19-vaccines-early-rollout-population-protection.html*.
11. Government of Canada. *National Advisory Committee on Immunization (NACI) statement: Recommendation on the use of the Pfizer-BioNTech COVID-19 vaccine (10 mcg) in children 5 to 11 years of age*. 2021; Available from: *https://www.canada.ca/en/public-health/services/immunization/national-advisory-committee-on-immunization-naci/recommendations-use-covid-19-vaccines/pfizer-biontech-10-mcg-children-5-11-years-age.html*.
12. Government of Canada. *NACI updated guidance on booster COVID-19 vaccine doses in Canada*. 2022 [cited 2021 December 3, 2021]; Available from: *https://www.canada.ca/en/public-health/services/immunization/national-advisory-committee-on-immunization-naci/guidance-booster-covid-19-vaccine-doses.html*.
13. Institut national de santé publique du Québec (INSPQ), *CONNECT: étude des contacts sociaux des Québécois*. 2020.
14. Brankston, G., et al., *Quantifying Contact Patterns in Response to COVID-19 Public Health Measures in Canada. (in preparation).* 2020.
15. Prem, K., A.R. Cook, and M. Jit, *Projecting social contact matrices in 152 countries using contact surveys and demographic data.* PLOS Computational Biology, 2017. **13**(9): p. e1005697.
16. Ferguson, N., et al., *Report 50: Hospitalisation risk for Omicron cases in Englans*. 2021, Imperial College.
17. UK Health Security Agency, *SARS-CoV-2 variants of concern and variants under investigation in England, Technical Briefing. Update on hospitalisation and vaccine effectiveness for Omicron VOC-21NOV-01 (B.1.1.529), 31 December 2021*. 2021.
18. Sheikh, A., et al., *Severity of Omicron variant of concern and vaccine effectiveness against symptomatic disease: national cohort with nested test negative design study in Scotland.* Pre-print, 2021.

4.2 SEIR COMPARTMENT MODEL: EXPLORING EFFECTS OF WANING IMMUNITY AND INCREASING BOOSTER ADMINISRATION

Key Points

- Simulations suggested that booster administration in 2021 may have significantly reduced hospitalisations during the Omicron wave.
- Scenarios in which there was rapid administration of additional boosters, to reach 90% of the eligible population, resulted in only a small additional reduction in hospitalisations during spring 2022.
- In scenarios where booster administration is rapidly deployed, the simulated fall 2022 resurgence, when a return to indoor contacts increases transmission risk, did not show a significant reduction in hospitalisations.

Note: Supplemental information on methods and/or results for this report is provided in Annex 5.2.5.

Background

In response to the rapid invasion and dominance of Omicron in Canada in late 2021 [1] and the recognition of waning efficacy of two doses of vaccination, it was recommended that booster doses be provided to the general population. Case surveillance data which had previously been obtained through testing of the general population was widely interrupted at a national level during the Omicron wave (late December 2021/early January 2022), which caused testing capacity to be exceeded. Since that time, hospitalisations have become one of the primary indicators of the status of the epidemic. However, hospital data lag infections by up to 14 days, due to the time it takes for infection to progress to hospitalization, and reporting delays, making them less than ideal for epidemic monitoring. Nevertheless, the impact of the virus on hospital capacity remains an important indicator throughout this pandemic.

This report presents updated simulations with, and without, the administration of booster vaccinations to examine the effect of boosters on the Omicron wave. Additionally, scenarios with different speeds and degrees of waning immunity along with different levels of booster administration are examined to see their effect on subsequent waves of COVID-19 following the most recent Omicron wave.

Methods

This study used an age-structured PHAC SEIR model [2] to examine the impact of COVID-19 in Canada. Details on the model structure and parameters can be found in Annex 5.2.5. The model was adjusted to age-specific domestic surveillance data using confirmed cases and daily hospital admissions up to December 20, 2021, and reported daily hospital admissions alone from December 21 to February 2, 2022.

Omicron transmission and calibration

Omicron cases were reported in Canada during the week of November 21, 2021 [3] and for the current simulations, community transmission of Omicron was assumed to have started at a national scale on November 26, 2021, with Omicron becoming dominant and displacing Delta approximately four weeks later. The intrinsic transmissibility of Omicron was assumed to be 1.75 times that of Delta [4] and vaccine effectiveness (VE) against infections and hospitalisation were implemented based on data from observational studies in the United Kingdom (UK) and Canada [5,6].

Omicron infections have a reduced probability of severe disease [7-11], assumed in this study to reduce the likelihood of severe outcomes requiring hospitalisation by 40% reduction (13% to 80% depending on the age) compared the Delta variant infections.

Given the nationally widespread interruption in testing of COVID-19 cases in the general population, hospitalisation rates used in the model by age were fixed to those observed during the first half of the Omicron wave (up to week of December 20). Contact rate parameters were then used to alter total infections (detected or not) to allow fitting of simulated daily hospitalisation incidence to observed hospitalisation data between December 20, 2021 to February 2, 2022.

Boosters during Omicron

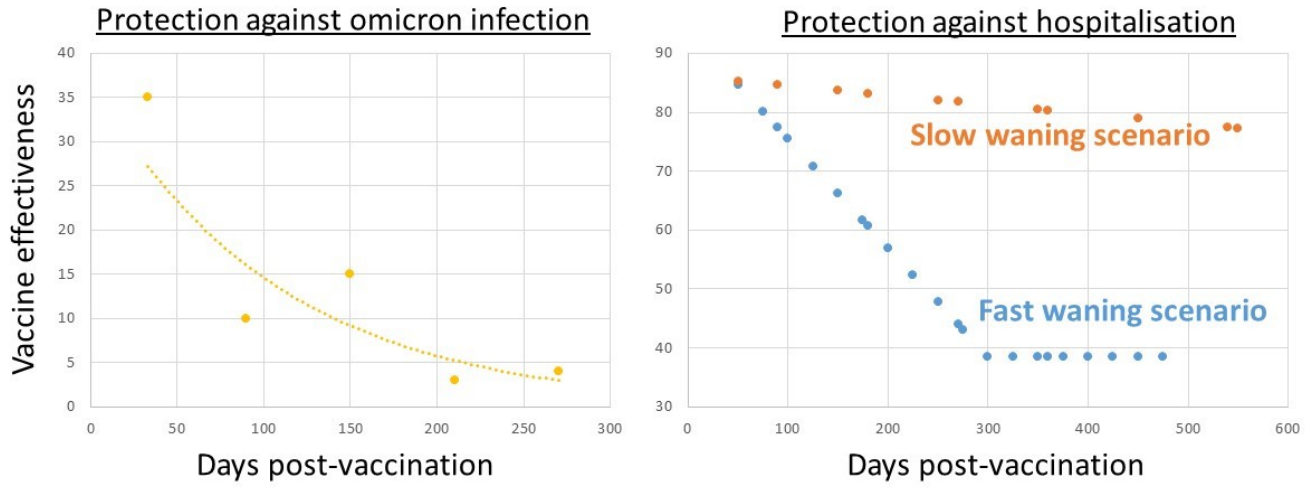
Boosters were rapidly rolled out during the Omicron wave. This coincides with a near 6 month elapse of time since second doses were administered for most of the population. Scenarios of vaccine administration (including boosters) were based on reported vaccination rates by age in Canada [12]. To study the impact of booster administration during the Omicron wave, a counterfactual scenario without boosters was used for comparison.

Waning immunity and increased boosters

Prior to Omicron, studies had suggested relatively strong protection against reinfection from immunity acquired post-infection [13]. Data from countries that used manufacturer-recommended short inter-dose intervals (three or four weeks for mRNA vaccines) showed signs of antibody waning approximately 6 months following the second dose of vaccination [14, 15] though protection via memory B-cells and T-cells against the risk of severe infection and death appeared relatively well maintained. Despite Omicron's recent arrival, some preliminary observations of vaccine effectiveness against Omicron infection and symptomatic infection suggest that significant waning of protection is observable within 3 months after the second dose of vaccine but there is very little information on the decline following a third dose as insufficient time has passed since Omicron infections have been observed [16]. Observation of waning immunity is confounded by reinfection risk when relying primarily on surveillance case data as a reference. The high rates of reinfection resulting from Omicron due to its immune escape capabilities have added to the difficulty in disentangling this information.

In the second set of simulations, immunity following infection or vaccination lasts 6 months prior to the arrival of Omicron. Once Omicron arrives in the model, waning of protection against Omicron, following two doses or a booster, is simulated in different scenarios using either an optimistic or a pessimistic set of waning assumptions. These scenarios were implemented using various lengths of stay and levels of protection in the different compartments of the model based on data shown in Figure 1 obtained from [5, 6].

Figure 1. Scenarios for waning immunity against infection and hospitalization. Data for these were obtained from the UK [5] and Canada [6].



For post-infection immunity, it was assumed that a period of full protection against transmission and severe outcomes lasted 2 months before immunity in recovered infected individuals begins to wane. Once waning began, however, it occurred as in the scenarios for post-vaccination immunity shown in Figure 1.

Vaccination coverage in all age groups was modelled based on vaccine data reported nationally [17] and data presented in reports from the Canadian Immunization Committee [17]. Scenarios with increased boosters assume rapid deployment of additional boosters to the eligible population 18 and older, over an approximate 1-month-long period from end of February until start of April, to reach 90% coverage.

Public health restrictive measures common to all simulations

Public health measures such as physical distancing, closures, telework and other restrictive measures are accounted for through the use of a stringency index parameter. This parameter is adjusted based onto the information presented in the Contribution Provided under Section 3: International Situational Awareness: COMPARING PUBLIC HEALTH MEASURES IN CANADA AND OTHER COUNTRIES with additional variance by age group conceptually representing age-specific behaviour and adherence to public health measures to adjust the model to observed data.

In all simulations the level of constraints on contacts at the start of January is set to ~37 % of pre-COVID-19 daily contact rates, gradually increased to 50% by February 15, after which it was kept at this level until until restrictions are lifted to 80% on March 1, 2022.

A summary of the modelled scenarios is shown in Table 1. All scenarios were run until the end of 2022.

Table 1. Summary characteristics defining the modelled scenarios.

Set 1. Effect of boosters during Omicron wave Scenario 1: Boosters administered as per reported vaccination distribution Scenario 2: No boosters		
Set 2. Effect of increased booster administration		
	"Pessimistic" waning assumptions	"Optimistic" waning assumptions
55% boosters	Scenario 3	Scenario 4
90% boosters	Scenario 5	Scenario 6

Results

In the first set of simulations (Figure 2), the administration of boosters during the Omicron wave reduced the height of the peak of daily hospitalisations by nearly 50% (from a peak ~1,900 daily hospitalisations without boosters to a peak of ~1,000 daily hospitalisations peak height with boosters). These results suggest that booster administration strongly contributed to reducing the impact of the Omicron wave on hospitalisations although uncertainty remains regarding the exact magnitude of this impact.

In the second set of simulations, the effects of different speeds of waning assumptions and levels of booster administration on the epidemic following the Omicron wave were compared. These simulations suggest a likely spring 2022 resurgence in daily hospitalisations as public health measures are lifted across the country followed by a potential fall 2022 wave when many activities return to indoors increasing the likelihood of indoor contacts and transmission risk (Figure 3).

Scenarios in which booster administration was increased to reach 90% coverage of the eligible population show a small reduction (nearly 20%) in the height of the spring 2022 hospitalisation peak over the scenario with current booster uptake (~55% of eligible population vaccinated with booster doses). However, this advantage and reduction in hospitalisations becomes even smaller by the next successive peak in fall 2022 under the current set of waning assumptions.

Scenarios comparing optimistic and pessimistic waning assumptions show a small reduction in hospitalisation wave heights during both the spring 2022 and fall 2022 peaks with the optimistic scenarios, but these reductions are not sufficiently different to change the general course of the simulated epidemic.

As there was a decrease in testing of the population at a national scale during the Omicron wave, there is a higher degree of uncertainty in many of the parameters used. In particular, in order to fit model simulations to observed hospitalisations, hospitalisation rates were fixed in the model to early Delta wave rates and only contact rates were modified for fitting after this point. This may have caused overestimation of cases during the Omicron wave.

Additionally, for this current set of simulations, the proportion of asymptomatic cases was kept the same as previously used in the earlier days of the epidemic (~30%). Given the reduced severity of Omicron, the proportion of asymptomatic infections may in fact be greater. If many more asymptomatic cases occurred during the Omicron wave than the proportion modelled in current simulations, then successive waves post-Omicron are likely to be smaller as fewer susceptible individuals are likely to be available. The height of successive peaks is directly linked to the number of susceptible individuals available for infection in the general population and the speed of waning of immunity.

Studies from the first year of the pandemic had suggested that infection conferred long lasting protection against re-infection. Since the arrival of Omicron, the duration of immunity following infection has yet to be determined.

Early data on vaccine-acquired immunity suggests that immunity against transmission may be short lived in the presence of Omicron. As a result, in these scenarios, a 2 month period of complete immunity against infection following natural infections was considered to occur prior to waning. If this length of time is longer, then the current simulations likely overestimate the magnitude of post-Omicron waves. Conversely, if this period of time is shorter, then post-Omicron waves will be higher in magnitude than those currently simulated.

Lastly, though the BA.2 Omicron variant is reportedly in circulation in Canada and gradually gaining dominance in many regions, this current set of simulations does not account for reported increased transmissibility of BA.2.

Conclusion

Simulations suggested that booster administration in 2021 may have significantly reduced the Omicron wave of hospitalisations. Scenarios suggested that a small reduction in hospitalisations during spring 2022 would be seen with rapid administration of additional boosters to reach the level of 90% in the eligible population. However, increasing booster uptake in March 2022 did not greatly affect the simulated fall 2022 resurgence, associated with increasing indoor contacts. There is a need to further study the timing of booster administration to determine optimal efficacy.

Figure 2. Daily hospitalized cases with or without booster administration with a lifting of restrictions so contacts are 80% of pre-COVID-19 levels on March 1st, 2022. Orange: scenario with boosters (to current coverage of 55% of the eligible population), mauve: scenario without boosters.

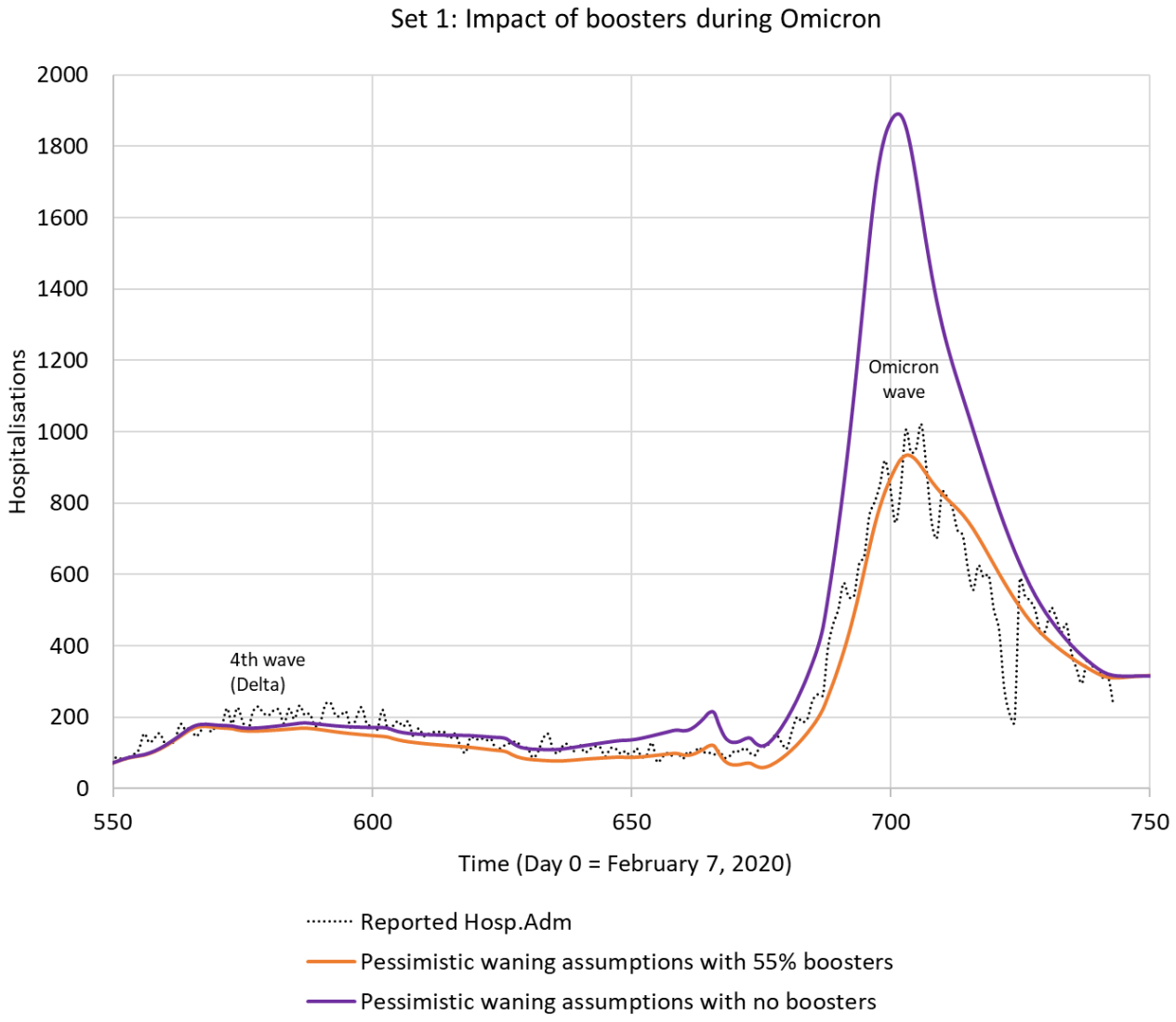
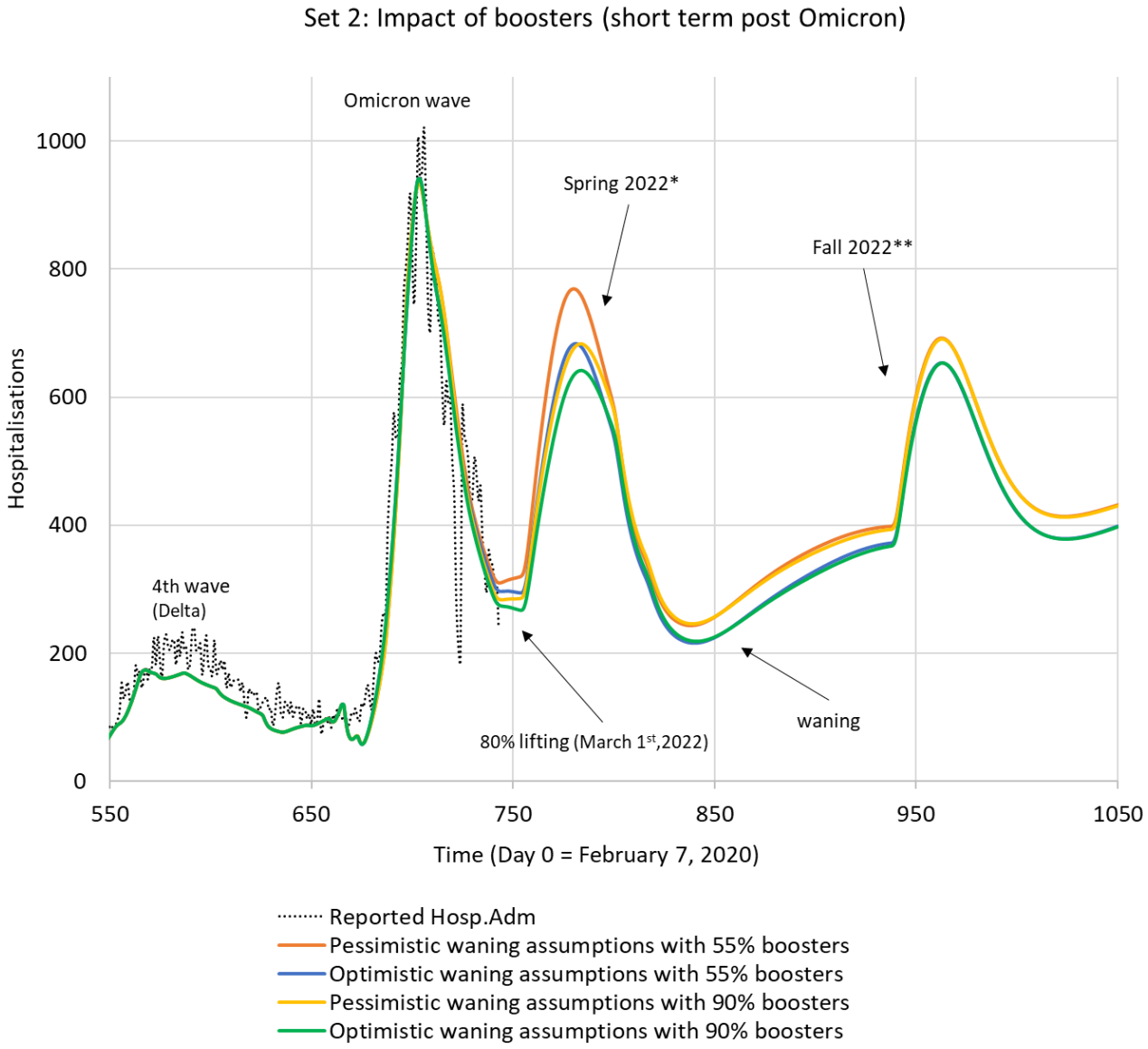


Figure 3. **Daily hospitalised cases for four different scenarios of waning and boosters with restrictions lifted up to 80% of pre-COVID-19 levels on March 1, 2022.** Orange: pessimistic waning scenario with 55% of eligible population given boosters, yellow: pessimistic waning scenario with 90% of eligible population given boosters, blue: optimistic waning scenario with 55% of eligible population given boosters, green: optimistic scenario with 90% of eligible population given boosters.



References

1. World Health Organization. 'Classification of Omicron (B.1.1.529): SARS-CoV-2 Variant of Concern' who.int: World Health Organization, 2021. https://www.who.int/news/item/26-11-2021-classification-of-Omicron-(b.1.1.529)-sars-cov-2-variant-of-concern
2. Ludwig A, B. P., Orpana H, Nadeau C, Diasparra M, Barnes J, Hennessy D, Otten A, Ogden N. (2020). "Assessing the impact of varying levels of case detection and contact tracing on COVID-19 transmission in

Canada during lifting of restrictive closures using a dynamic compartmental model." Can Commun Dis Rep 46(11/12): 409-421.
3. Government of Canada, 2021. COVID-19 daily epidemiology update. https://health-infobase.canada.ca/covid-19/epidemiological-summary-covid-19-cases.html
4. Pearson, C. et al., Omicron spread in South Africa – Growth, Transmissibility, & Immune Escape Estimates. Epidemics conference presentation.
5. United Kingdom Health Security Agency. COVID-19 vaccine surveillance report. Week 11, 17 March 2022. UKHSA gateway number GOV-11226
6. Buchan SA, Chung H, Brown KA, et al. Effectiveness of COVID-19 vaccines against Omicron or delta infection. medRxiv. 2022:2021.12.30.21268565. DOI:10.1101/2021.12.30.21268565.
7. Sheikh, A, Kerr, S, Woolhouse, M, McMenamin, J & Robertson, C 2021 'Severity of Omicron variant of concern and vaccine effectiveness against symptomatic disease: national cohort with nested test negative design study in Scotland'
8. Ulloa AC, Buchan SA, Daneman N, et al. Early estimates of SARS-CoV-2 Omicron variant severity based on a matched cohort study, ontario, canada. medRxiv. 2021:2021.12.24.21268382. DOI:10.1101/2021.12.24.21268382.
9. Ontario Agency for Health Protection and Promotion (Public Health Ontario), Ontario Agency for Health Protection and Promotion (Public Health Ontario),. Early estimates of Omicron severity in Ontario based on a matched cohort study, November 22 to December 25, 2021. Toronto, ON: Queen's Printer for Ontario; 2021. Report No.: December 25, 2021URL: https://www.publichealthontario.ca/-/media/documents/ncov/epi/covid-19-epi-enhanced-estimates-Omicronseverity-study.pdf?sc_lang=en
10. Christensen PA, Olsen RJ, Long SW, et al. Early signals of significantly increased vaccine breakthrough, decreased hospitalization rates, and less severe disease in patients with COVID-19 caused by the Omicron variant of SARS-CoV-2 in houston, texas. medRxiv. 2022:2021.12.30.21268560. DOI:10.1101/2021.12.30.21268560.
11. Wang L, Berger NA, davis PB, et al. Comparison of outcomes from COVID infection in pediatric and adult patients before and after the emergence of Omicron. medRxiv. 2022:2021.12.30.21268495. DOI:10.1101/2021.12.30.21268495.
12. Government of Canada, 2021.COVID-19 vaccination in Canada. https://health-infobase.canada.ca/covid-19/vaccination-coverage/
13. Turner, J.S., Kim, W., Kalaidina, E. *et al.* SARS-CoV-2 infection induces long-lived bone marrow plasma cells in humans. *Nature* **595,** 421–425 (2021). *https://doi.org/10.1038/s41586-021-03647-4*
14. Tartof SY et al.(2021). *"*Effectiveness of mRNA BNT162b2 COVID-19 vaccine up to 6 months in a large integrated health system in the USA: as retrospective cohort study" The Lancet 398(10309):1407-1416 *https://doi.org/10.1016/S0140-6736(21)02183-8*
15. Chemaitelly, H et al., (2021). "Waning of BNT162b2 Vaccine protection against SARS-CoV-2 infection in Qatar". NEJM DOI: 10.1056/NEJMoa2114114
16. Kwong, J. et al., "Effectiveness of COVID-19 vaccines over time in Ontario", COVID-19 Immunity Task Force presentation, January 24, 2022
17. Government of Canada, 2021.COVID-19 vaccination in Canada. https://health-infobase.canada.ca/covid-19/vaccination-coverage/
18. COVID-19 vaccination coverage in Canada, Weekly report to the Canadian Immunization Committee (CIC), January 07, 2022.

5 ANNEXES

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5.2 SUPPLEMENTAL MATERIALS

The following section contains supplemental methods and results related to the models of the report.

5.2.1 Short range of reported cases and deaths in Canada by the Generalized Richards Model (GRM)

Note: The supplemental materials provided in this section are related to Section 2.2 of this report.

Methods

The Generalized Richards Model (GRM) was used at this stage of the pandemic to project future cases and deaths in the near-term. This model can capture the possibility of early sub-exponential growth epidemics (ranging from constant incidence, polynomial, and exponential growth dynamics). It generally fits a wide range of S-shaped growth curves, more so than the logistic model due to its accommodation of situations where the growth curve is asymmetrical. An illustration of the use of this model to predict cases in Canada (and its comparison with other empirical models) is available at https://doi.org/10.1016/j.epidem.2021.100457.

Limitations

The models used for near-term forecasting do not explicitly consider the mechanisms of transmission of COVID-19, including human behaviours and response to the epidemic. Future growth of the epidemic is entirely based on historic reported case counts. As such, these models do not explicitly consider the impacts of recently implemented or de-escalation of mitigation measures (social distancing, facility closures, etc.), and the effects of such measures do not influence projections until actually observed in the reported surveillance case data. The models also do not account for any delays in testing, testing backlogs, changes to number of tests performed daily, changes to testing eligibility, recent introductions of new variants of concern, etc.

5.2.2 Long range forecast of reported cases in Canada using dynamic modelling (PHAC-McMaster University)

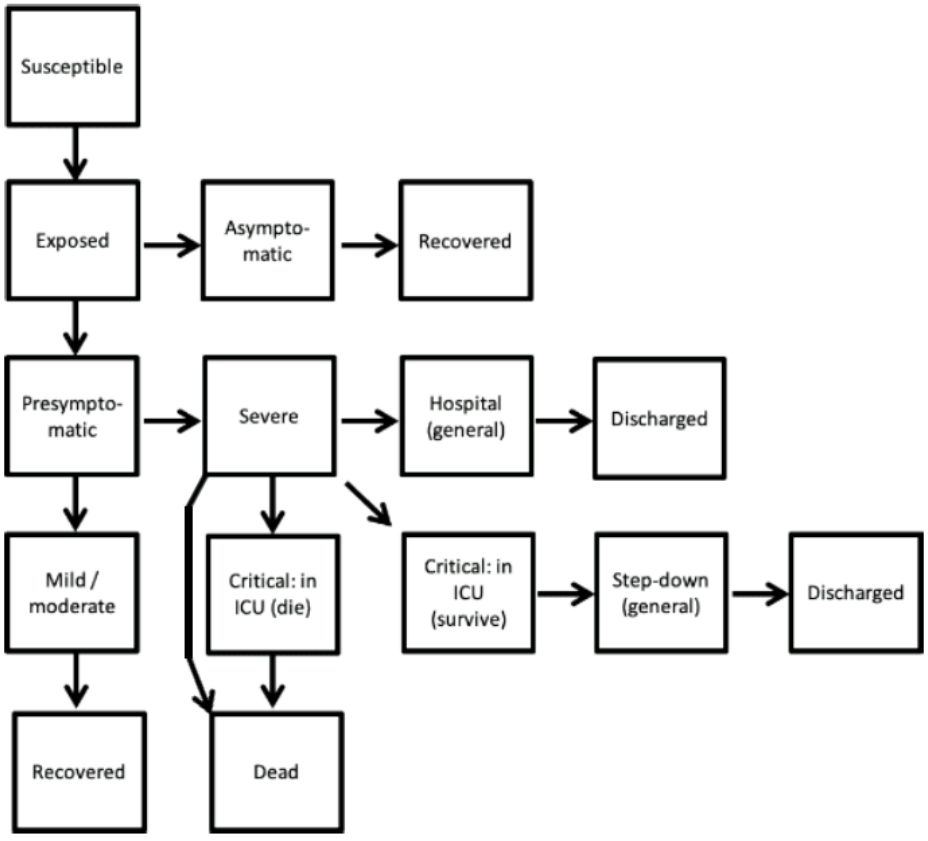
Note: The supplemental materials provided in this section are related to Section 2.3 of this report.

Methods

Model design

The PHAC-McMaster University model is a SEIR model with additional compartments reflecting the biology of SARS-CoV-2 infections and aspects of the healthcare system relevant to treating COVID-19. The COVID-19-specific compartmental structure is dividing infection compartments into asymptomatic (a), presymptomatic (p), mildly/moderately symptomatic (m), or severely symptomatic (s); and compartments for hospitalised individuals in acute care or intensive care (Figure A-1).

Figure A-1. PHAC-McMaster University model compartmental flow chart.

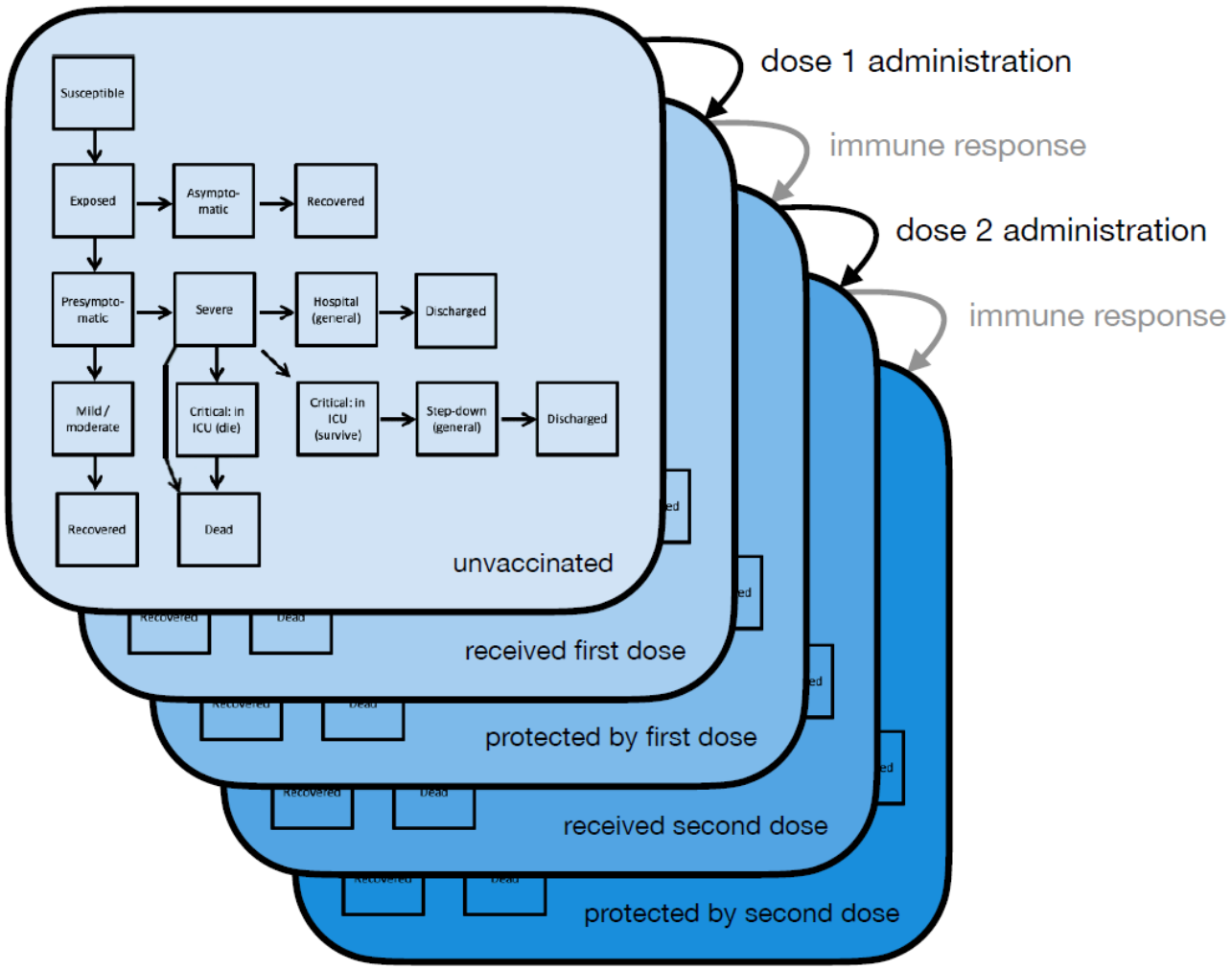


The model also includes a two-dose vaccination mechanism with five vaccination strata: unvaccinated, received a first dose of a vaccine (but is not yet protected due to the delay in immune response to the shot), protected by a first dose of a vaccine, received a second dose, and protected by a second dose. Each vaccination stratum has its own set of epidemiological compartments so that disease parameters can be adjusted to reflect reduced severity of breakthrough infections after each dose (Figure A-2). To incorporate booster effects, it is assumed that the VE of boosters brings protection back to full 2nd dose levels. To incorporate waning post-infection immunity, all the

recovered individuals before Match 15, 2020 were added back to the susceptible class. A full three-dose vaccination model is in development.

The model allows for time-varying, piecewise constant changes in the effective transmission rate, β(t), to account for changes in public health interventions over time and time-varying proportion of severe infections. For each province, a sequence of dates upon which major changes to public health policy were made is specified, and re-estimate the effective transmission rate in the periods between each of these dates (Table A-1).

Figure A-2. PHAC-McMaster University model vaccination strata.



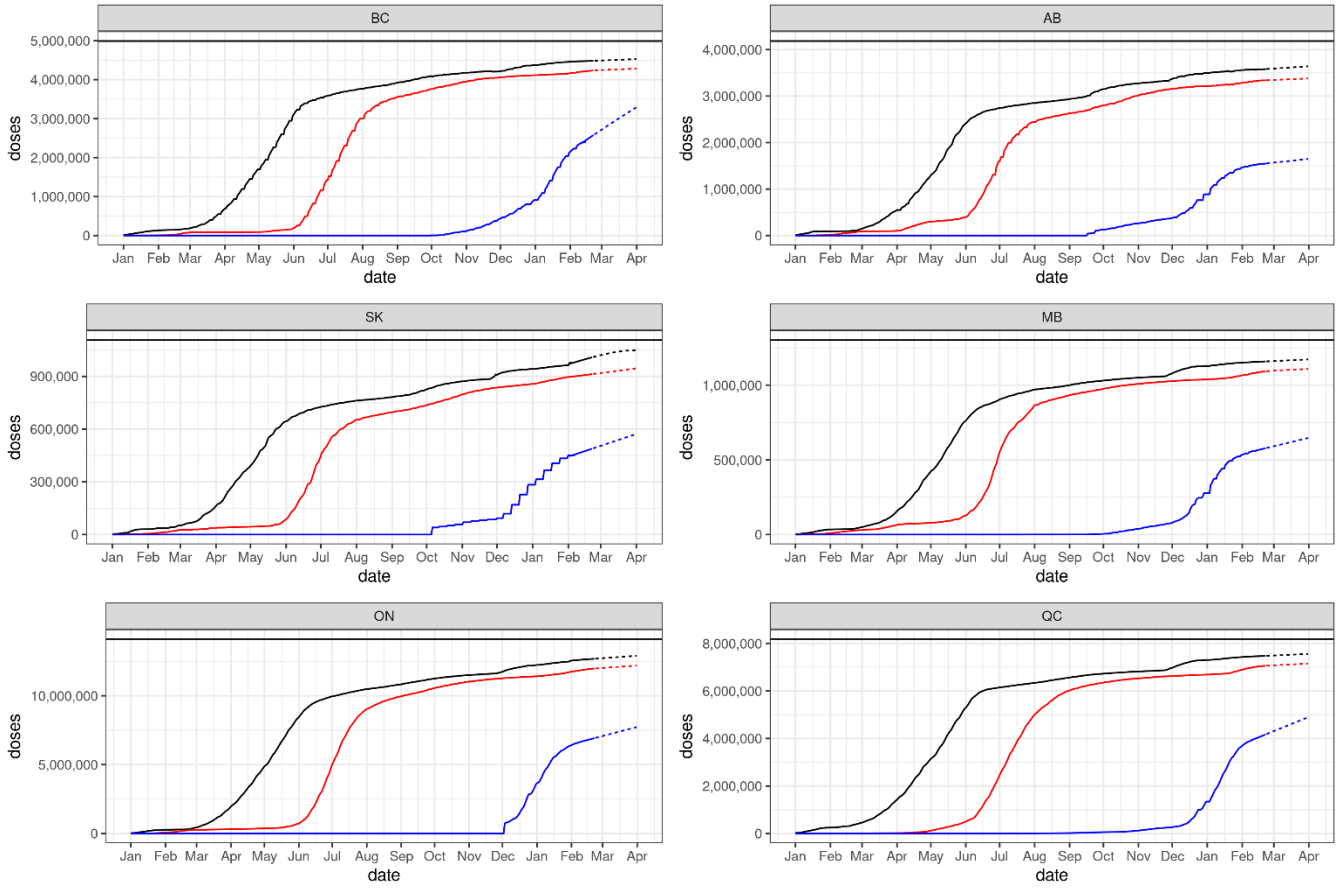
Calibration

The model framework allows simultaneously fitting to any number of observed reporting time series (e.g. reported cases, hospitalizations, ICU admissions, deaths). Calibration is completed using maximum likelihood estimation by matching deterministic model trajectories to the given reporting time series (assuming negative binominal observation error). Any increased transmissibility due to the presence of variants of concern (VOC) is accounted for implicitly when estimating time-varying changes to the effective transmission rate, though in addition,

increases to the transmission rate due to increases in VOC prevalence in the last estimation period for the transmission rate before forecast (as well as in the forecast period) are modelled.

Observed daily first, second dose and booster vaccine administration counts are included in the calibration process by converting these daily counts to rates per non-symptomatic individual in the relevant vaccine stratum simulating the distribution of vaccines to eligible populations. A vaccinated individual will take an average of 14 days to mount a protective immune response from vaccination. Against the Alpha VOC (B.1.1.7), the first dose of a vaccine is assumed to be 60% effective at blocking transmission, while the second dose is assumed to be 90% effective. Vaccine efficacy is reduced in proportion to the share of reported cases attributed to the Delta VOC (B.1.617.2) to 30% after first dose and 80% after second dose and remains 80% after boosting. For Omicron, it is assumed that it is half as effective as Delta implying 15% after first dose, 40% after second dose and 70% after boosting. The probability of asymptomatic infection is higher with each dose of the vaccine, and severe infections do not occur in individuals that have received at least a first dose.

Figure A-3. Cumulative number of vaccines administered for the six major provinces. The solid lines are the daily cumulative counts and dashed lines are the projections. The black horizontal is the eligible population. Black, red and blue trajectories are population with at least 1 dose, two doses and boosters, respectively.



Long term projections

Five hundred realizations of the calibrated model are used to project reported cases, hospital admission and occupancy for 30 days forward in time based on various scenarios. Each scenario is based on taking the effective

transmission rate estimated in the period immediately before the projection date and multiplying it by a to reflect possible changes in transmission following a loosening or strengthening of public health measures.

Competition between the dominant Delta VOC and the invading Omicron VOC is assumed, resulting in logistic growth of the proportion of reported cases caused by Omicron with a selection coefficient of 0.3/day.

Future vaccination is projected by a saturating function that accounts for current vaccination rate, lower demand and hesitancy. A 95%, 90% and 85% threshold of the eligible population (ages 5+) was added for first, second and booster dose respectively so the remainder will be the hesitancy population (Figure A-3).

Table A-1. Key dates for reopening and reintroduction of public health measures for the six major provinces.

Province	Date	Details
British Columbia	May 25, 2021	Step 1 of 4 reopening
	June 15, 2021	Step 2 reopening
	July 1, 2021	Step 3 reopening
	August 20, 2021	Masking and additional restrictions reintroduced in Central Okanagan region
	September 13, 2021	BC Vaccine card now in effect
	September 28, 2021	New health restrictions for eastern Fraser Valley amid low vaccination rates
	October 14, 2021	Additional restrictions for northern region
	October 25, 2021	Restrictions and capacity limits lifted for inside organised events and gathering where BC Vaccine card in place and proof of vaccination checked
	December 20, 2021	Increase public health restrictions and capacity limits
	January 20, 2022	Gym reopening
	February 17, 2022	Lifting capacity limits, reopening bars and allowing dancing
	March 17, 2022	Restaurants, bars, pubs and nightclubs can operate at hull capacity without limits. Indoor mask order lifted and restrictions eased.
Alberta	June 1, 2021	Stage 1 reopening
	June 10, 2021	Stage 2 reopening
	July 1, 2021	Final stage reopening
	September 3, 2021	Public health measures reintroduced including mandatory masking for indoor spaces and workplaces; and ending alcohol service in establishment
	September 20, 2021	Start of Restrictions Exemption Program and new province-wide public health measures
	October 25, 2021	Full vaccination required for 12+ to access restaurants, movies, sporting events and other businesses operating under the Restrictions Exemption Program
	November 15, 2021	Only proof of vaccination with QR codes will be accepted (with some exceptions) at venues and businesses taking part in Restrictions Exemption Program
	December 24, 2021	Increase public health restrictions and capacity limits

	February 8, 2022	Introduced 3-step approach for lifting public health measures; will move to Step 1: removal of Restrictions Exemption Program and capacity limits at 500 capacity venues
	March 1, 2022	Beginning Step 2 which includes ending capacity and gathering limits, remaining school requirements; and public masking requirements except in high-risk settings
Saskatchewan	May 30, 2021	Step 1 reopening
	June 20, 2021	Step 2 reopening
	July 11, 2021	Step 3 reopening
	September 17, 2021	Interim province-wide mandatory masking order implemented for all indoor public spaces
	October 1, 2021	Proof of vaccination or negative test to access certain spaces and activities
	October 18, 2021	Proof of vaccination or negative test to access certain spaces and activities
	October 26, 2021	Expanding COVID-19 vaccine availability through physician offices
	December 10, 2021	Increase public health restrictions and capacity limits
	February 28, 2022	Previous public health order will be removed on Feb 28
	March 1, 2022	Masking mandate and remaining public health orders lifted
Manitoba	June 12, 2021	Outdoor gatherings will be permitted on private and public spaces
	June 26, 2021	Stage 1 reopening
	July 17, 2021	Stage 2 reopening
	August 28, 2021	Masks required at all indoor public spaces
	September 3, 2021	Vaccine passport and indoor mask will be required to participate in certain events/activities with exceptions for ineligible children
	October 12, 2021	Additional restrictions for Southern Health region
	October 21, 2021	Ended state of emergency
	November 12, 2021	Additional restrictions in place
	December 21, 2021	Increase public health restrictions and capacity limits
	February 15, 2022	Capacity limits eliminated in venues and proof of vaccination will no longer be required.
	March 1, 2022	New public health orders which remove proof of vaccination requirements for public places
	March 15, 2022	Remaining public health orders lifted
Ontario	June 11, 2021	Step 1 reopening
	June 30, 2021	Step 2 reopening
	July 16, 2021	Step 3 reopening
	August 18, 2021	Pausing exit from Roadmap to Reopen in response to Delta variant
	September 25, 2021	Capacity limits increased in many indoor settings where proof of vaccination is required
	October 9, 2021	Allowing full capacity at spectator sports, entertainment, event, racetrack, and film production spaces
	October 25, 2021	Capacity limits for bars, restaurants and gyms lifted
	November 25, 2021	Additional restrictions in Northern Ontario regions
	December 19, 2021	Increase public health restrictions and capacity limits

	January 31, 2022	Begin easing COVID-19 restrictions, with plan to lift most measure by mid-March - restaurants, retailers, museums will be able to reopen with 50% capacity - indoor social gatherings increase to 25, and 100 people outdoors
	February 17, 2022	Moving to the next phase of reopening including increasing social gatherings to 50, restaurants, cinemas can operate without any capacity limits, 50% capacity in sports and arts venues
	March 1, 2022	Proof of vaccine mandates lifted
	March 21, 2022	Mask mandates lifted for most spaces such as schools, restaurants gyms and stores
Quebec	May 28, 2021	Reopening plan started
	June 11, 2021	Bar terraces reopen
	July 12, 2021	No limit capacity in stores as long as one meter distance between clients is maintained
	September 1, 2021	Vaccine passport starts for public events, bars, restaurants, gyms
	September 15, 2021	Enforcement of passports commences
	September 27, 2021	Individuals living in private seniors' residence in regions with high transmission rates will be required to wear mask in common areas
	October 8, 2021	Increase indoor capacity
	October 14, 2021	Mandatory vaccination passport to access health facilities and living environments; easing measures for restaurants and bars
	October 22, 2021	Guidelines for Halloween; limits for indoor gathering
	November 15, 2021	QC public servants will return to the office; dancing and singing will be allowed in bars and restaurants
	December 20, 2021	Increase public health restrictions and capacity limits
	January 31, 2022	Beginning to ease measures
	February 7, 2022	Movie theatres entertainment venues and places of worship can reopen at 50% capacity
	February 12, 2022	Private gatherings no longer have any restrictions, restaurants can seat up to 10 per table.
	February 14, 2022	Gyms, spas reopen at limited capacity; sports and artistic activities for adults allowed for groups of 25
	February 16, 2022	Proof of vaccination no longer required for large surface stores
	February 21, 2022	Proof of vaccination no longer required for funeral and places of worship; Retail businesses reopen at full capacity places of worship remains at 50% capacity, with a max of 500 people
	March 1, 2022	Employees no longer required to wear mask when sitting at their desk; Working from home will no longer be mandatory; capacity limits increase for large venues and bars
	March 12, 2022	Close contacts of individuals that tested positive are no longer required to isolate; Restaurants, bars, large venues allowed to operate at full capacity; Proof of vaccination will be phased out entirely

5.2.3 Importation risk by air and land

Note: The supplemental materials provided in this section are related to Section 3.1 of this report.

Methods

Model structure

The model takes into account: a) air and land travel volumes, b) types of travellers, c) pre-arrival test policy, d) natural immunity and vaccination coverage, e) underreporting correction factor, and f) region-specific daily probability of infection. Based on this information, the model calculates the expected number of passengers arriving infected in Canada and the number of infected passengers by variant. Modelling is done at the country level for air travellers, and at the American state level for land travellers.

Types of travellers

For the purpose of these analyses, travellers are separated into two categories. The first type of traveller is referred to as a "Canadian", *CND*, which describes a person who resides in Canada. CNDs are assumed to have spent all their time in Canada from the start of the pandemic except for a visit of t_c days to country *c* where infection can occur and cause importation risk. The second type of traveller is called a "foreign traveller", *FT*. These travellers are assumed to have spent all their time in country *c* since the start of the pandemic and then visit Canada and contribute to importation risk. The value of t_c for CNDs is described by a normal distribution $N(15, 2)$ under the assumption that most Canadians have approximately 15 days of annual leave to spend in country *c* [1]. For FTs t_c is the time from the start of the pandemic to date.

Air and land travel volumes

Current daily air travel volumes expected into Canada are provided by the Canadian Border Services Agency (CBSA) from the Advanced Passenger Information (API) database. While these data describe the expected travel volumes to Canada from the embarkation country (i.e. country from where travel to Canada was started), they are not the actual count of arriving passengers, and represent an overestimation of the actual travel volume due to cancelled, delayed, or missed flights. To correct for this overestimation, the weekly percent reduction (14% for the week of March 13-19, 2022) between the overall API travel volume and the actual total number of travellers who have crossed the border (derived from passage data provided by CBSA) is applied uniformly to the API travel volume for each country of departure. Data from CBSA are also stratified by traveller type. Within the CBSA data, the issuing country of the travel document presented at the time of ticket purchase is used as a proxy to characterise CNDs and FTs. Travel volumes for air travel at the airport level for the entire travel itinerary are provided from the International Air Transport Authority (IATA). CBSA and IATA data have daily and monthly resolutions, respectively. Furthermore, the IATA data are received with a 60-day delay. Therefore, to calculate importation risk at the port of entry (PoE) level in Canada for air travellers, the country arrival total from CBSA is distributed in proportion to airport totals reported by IATA.

Current land travel volume data are also provided by CBSA as the daily volume of travellers, including commercial traffic, entering at Canada's land PoEs. The embarkation state (i.e. American state from where travel to Canada was started) is derived from an additional CBSA dataset that provides the daily count of license plates on vehicles entering Canada at each land PoE. It is assumed that embarkation location for travellers in vehicles with American

license plates are from the state of the license plate. For travellers in vehicles with Canadian license plates, the embarkation location is assumed to be the US state adjoining the PoE.

Pre-arrival test policy

A test policy enacted on January 7, 2021 requires most travellers to provide a negative PCR COVID-19 test result up to 72 hours prior to departure to Canada (hereafter referred to as non-exempt travellers). Essential travellers are largely exempt from the pre-departure testing policy (hereafter referred as exempt travellers). The pre-departure testing policy has since been updated such that as of February 28, 2022, non-exempt travellers entering Canada may show proof of either a negative PCR test result (performed within 72 hours of departure), or a negative rapid antigen test result (performed the day prior to departure). Given the increased affordability and accessibility of the rapid antigen test, it was assumed that 95% of non-exempt travellers would opt for the rapid antigen test rather than the PCR test. In the model, the delay between the PCR test and departure to Canada is assumed to be 3 days, and the sensitivity of the PCR test, *Se*, is set at 60% to account for variation in the test sensitivity with respect to time since infection [2]. A sensitivity of 37% is assumed for the rapid antigen COVID-19 tests, with a 1 day interval between the test and departure to Canada [3].Travel volume data for the travellers who are non-exempt from pre-arrival testing for each country or point of entry (USA), for both land and air travel modes are provided by ArriveCAN and ContactTrace at the weekly level. The proportion of exempt travellers is calculated as:

$$1 - \frac{Number\ non{-}exempt_{ArriveCan}}{Total\ travel\ volume_{CBSA}}.$$

For non-exempt travellers, travellers in the ArriveCan database who indicate that they are "returning to Canada" are used to proxy *Canadians,* while all other travellers are proxied by the term *foreign traveller.* For exempt travellers, the proportion of CNDs and FTs by country or point of entry (US) are calculated from the CBSA's API database (see section above "*Air and land travel volumes*").

Natural immunity and vaccination coverage (including updates regarding the Omicron variant)

The probability of a traveller importing infection into Canada from country *c* depends in part on whether they have already recovered from infection with COVID-19 and have developed immunity against re-infection since the start of the pandemic and whether they have been vaccinated and have successfully developed immunity against infection. This model assumes that the immunity developed from natural infection and vaccination does not wane over time.

The model has been updated to account for the Omicron variant, which partially evades the protection afforded by both vaccination and previous infection with other variants. For simplicity, it is assumed that Omicron became the dominant variant globally on December 1, 2021 (hereafter referred to as the *Omicron period*). Prior to that date, it is assumed that all infections resulted from a variant other than Omicron (hereafter referred to as the *pre-Omicron period*). Similar to our assumptions in the previous reports, during the pre-Omicron period, all infections lead to a 100% protection against re-infection. Subsequently, given the immune escape properties of the Omicron variant, only 35% of those infected prior to December 2021 are assumed to maintain immunity against infection with Omicron. The proportion of the population that is protected against re-infection on day *d* in country *c* is therefore equal to:

$$Pprotected_{c,d} = \begin{cases} \dfrac{Infected_{c,d-1}}{Pop_{c,2020}} & pre-Omicron\ period \\ \dfrac{Infected_{c,Nov\ 31,2021} * 0.35 + Infected_{c,Dec\ 1,2021\ to\ d-1}}{Pop_{c,2020}} & Omicron\ period \end{cases} \quad (1)$$

Where $Infected_{c,d-1}$ is the number of people infected prior to day *d-1*, $Infected_{c,Nov\ 31,2021}$ is the number of people infected prior to December 1, 2021, $Infected_{c,Dec\ 1,2021\ to\ d-1}$ is the number of people infected between December 1, 2021 and day *d-1*, and $Pop_{c,2020}$ is the 2020 population estimate in country c.

Additionally, the vaccine efficacies are assumed to decrease after December 1, 2021. To account for variability in the efficacy between vaccine candidates that are used across the world, it is assumed that vaccine efficacy against infection follows a normal distribution with a standard deviation of 1.5% (mean values are provided in Table A-1). A slightly higher vaccine efficacy is used for the USA and Canada since the majority of vaccines administered in these countries are of the type mRNA, which has been found to provide better protection then other vaccines [4].

Table A-1. Vaccine efficacy against infection for each vaccine status used in the importation risk model.

Government of Canada (GoC) approval status	Country	Assumption	Vaccine status	Mean VE estimate	Reference
Non-exempt travellers[a]					
Non GoC-approved	a) All countries	Assumed to be equal to VE for AZ	Partially vaccinated	**Pre-Omicron:** 0.30 **Omicron:** 0.035[d]	[4-6] calculated
			Fully vaccinated	**Pre-Omicron:** 0.60 **Omicron:** 0.075	[4-7] [8]
			Boosted	**Pre-Omicron:** 0.60[e] **Omicron:** 0.56[f]	[9] calculated
GoC-approved	b) USA and Canada	Assumed to be equal to VE for mRNA vaccines	Partially vaccinated[c]	**Pre-Omicron:** 0.35 **Omicron:** 0.15[d]	[6] calculated
			Fully vaccinated	**Pre-Omicron:** 0.82 **Omicron:** 0.34	[6, 10] [8]
			Boosted	**Pre-Omicron:** 0.82[e] **Omicron:** 0.70	[9] [11]
	c) Non-USA foreign countries	Assumed to be equal to the average of AZ VE	Partially vaccinated[c]	**Pre-Omicron:** 0.32 **Omicron:** 0.09	calculated
			Fully vaccinated	**Pre-Omicron:** 0.71 **Omicron:** 0.21	

		(a) and mRNA VE (b)	Boosted	**Pre-Omicron:** 0.71 **Omicron:** 0.63	
Mixture of GoC- and non GoC-approved	d) All countries	Assumed to be equal to the average of non GoC-approved VE (a) and GoC-approved VE (c)	Fully vaccinated	**Pre-Omicron:** 0.66 **Omicron:** 0.14	calculated
			Boosted	**Pre-Omicron:** 0.66 **Omicron:** 0.60	
Exempt travellers[b]					
Data unavailable	e) USA and Canada	Assumed to be equal to VE for mRNA vaccines (a)	Partially vaccinated	**Pre-Omicron:** 0.35 **Omicron:** 0.15[d]	[6] calculated
			Fully vaccinated	**Pre-Omicron:** 0.82 **Omicron:** 0.34	[6, 10] [8]
			Boosted	**Pre-Omicron:** 0.82[e] **Omicron:** 0.70	[9] [11]
Data unavailable	f) Non-USA foreign countries	Assumed to be equal to the average of non GoC-approved VE (a) and GoC-approved VE (c)	Partially vaccinated	**Pre-Omicron:** 0.31 **Omicron:** 0.06	calculated
			Fully vaccinated	**Pre-Omicron:** 0.66 **Omicron:** 0.14	
			Boosted	**Pre-Omicron:** 0.66 **Omicron:** 0.60	

AZ = Astrazeneca; VE = Vaccine efficacy

[a] The proportion of travellers in each vaccine status category were based on ArriveCan and ContactTrace

[b] The proportion of travellers in each vaccine status category were based on country-specific vaccine coverage data [12]

[c] Includes travellers that received their second dose within 14 days prior to travel to Canada

[d] Calculated using the Pre-Omicron/Omicron ratio of the VE for fully vaccinated individuals with that same vaccine

[e] Prior to December 2021, it is assumed that travellers who have received the booster vaccination have similar protection against infection to those who are fully vaccinated [9].

[f] Calculated using the mRNA Booster/dose2 VE ratio

In the present analyses, vaccine efficacy corresponds to the probability that a vaccinated individual develops complete immunity against infection (i.e. 0% probability of getting infected). Hereafter, the term "probability of being successfully vaccinated", $Vacc_{c,d}$, is used to describe the probability that a traveller from country *c* has been vaccinated and has successfully developed immunity against infection on day *d*. The probability of a traveller being successfully vaccinated is $Vacc_{h,d}$ for CND travellers (home Country *h*).

Non-exempt travellers are required to show proof of vaccination status when entering Canada. The proportion of non-exempt travellers who are fully vaccinated with Government of Canada approved vaccines, partially vaccinated with Government of Canada approved vaccines, fully vaccinated with non-Government of Canada approved vaccines, partially vaccinated with non-Government of Canada approved vaccines, fully vaccinated with a mixture of Government of Canada and non-Government of Canada approved vaccines and unvaccinated are

calculated each week from ArriveCan and ContactTrace data. The proportion of fully vaccinated travellers who have received a booster is assumed to be proportional to that of the respective country of origin. For each vaccine status, the probability of a traveller being successfully vaccinated, $Vacc_{c,d}$, is equal to the efficacy of the vaccine for the corresponding dose received in country *c* (Table A-1).

Data regarding vaccine status is not available for exempt travellers. Therefore, the probability of a traveller being successfully vaccinated is assumed to be proportional to the vaccine coverage on day *d* in country *c* ($Prop_{c,d}$), and vaccine efficacy (VE_c) for dose 1, dose 2, and the booster (Table A-1):

$$Vacc_{c,d} = Prop_{c,d,dose1} \times VE_{c,dose1} + Prop_{c,d,dose2} \times VE_{c,dose2} + Prop_{c,d,booster} \times VE_{c,booster} \quad (2)$$

The vaccine coverage in each country is extracted from an openly available dataset on the country-specific cumulative number of COVID-19 vaccinations, updated on a daily basis with the most recent official numbers (https://ourworldindata.org/covid-vaccinations). As of January 15, 2022, a vaccine mandate requiring exempt FT entering Canada to be fully vaccinated was implemented. Therefore, in the model, a large proportion of exempt FT travelling by air (92% for the week of March 13-19, 2022) and FT and CND (a similar mandate was enacted for CNDs entering the USA) exempt travellers entering by land (96% for the week of March 13-19, 2022) are assumed to be fully vaccinated, with or without a booster (in Eq.2, $Prop_{c,d,dose1} = 0$ and $Prop_{c,d,dose2} + Prop_{c,d,dose3} = 100\%$). For these travellers, the probability of having received a booster is equal to the proportion of fully vaccinated people in country c who have also received a booster.

Underreporting correction factor

The number of confirmed cases reported from national surveillance systems underestimates the true population prevalence because of inadequacies in the healthcare system to detect, test and report cases, including a lower probability of observing asymptomatic cases. Therefore, a method adapted from [13], was used to calculate a time varying correction factor, CF_t. Briefly, Wu et al. (2020) [13], developed a semi-Bayesian probabilistic bias analysis based on the population size, reported cases, and reported number of COVID-19 tests to estimate the actual number of cases for each state in the United States (US). This method was modified to estimate the CF_t for each country and US state, taking into account the temporal decrease in the susceptible population due to increasing cumulative case counts, the vaccine coverage, and the time-varying, variant-specific probability of reinfection. The CF_t for a given country during a specific time period was calculated by dividing the number of estimated cases by the number of reported cases.

As most data was unavailable early in the pandemic, daily country- and state-specific data on the number vaccinated [12, 14, 15], the number tested [12, 14, 16, 17], and the number of new cases [12, 14, 17, 18] were used to calculate the CF_t from March 2020 onwards. Linear interpolation was used to estimate the number tested or vaccinated in the case of missing data.

As described in [13], the estimation method provides unstable results for settings with low testing rates. To circumvent this issue, the data were aggregated from March-August 2020, and in one month intervals thereafter. If insufficient data were available due to ongoing data collection, the data was aggregated for a four-week period, ending at the date with the most recent data.

The susceptible population size for each time period for country *c* was calculated as a function of the 2020 population estimates ($Pop_{c,2020}$) [12, 19, 20], the reported proportion protected against infection

($Pprotected_{c,d}$, , see Eq.1) and the proportion of people successfully vaccinated ($\mathrm{Vacc}_{c,d}$, see Eq.2 and Table A-1,):

$$SPop_{c,d} = Pop_{c,2020} \times \left(1 - Pprotected_{c,d}\right) \times \left(1 - Vacc_{c,d}\right) \quad (3)$$

In rare instances, the estimated CF_t value was below 1, in which case a ratio of 1 was assumed. Based on a visual exploration of the estimated CF_t values, a maximum threshold value of 80 was arbitrarily chosen and any estimated value above this threshold was discarded. Any missing CF_t values due to data filtering with respect to the threshold, or insufficient data was replaced with the median value across all available CF_t for the respective country or state, whenever possible. For countries in which all CF_t values were unavailable, a regression modelling approach was used to estimate the CF_t (dependent variable) on the country-specific 2019 Growth National Income (GNI) per capita [21] . The GNI was a proxy for the effectiveness of the country's surveillance system to detect, test and report COVID-19 cases. The regression model was run for each time period, and the average Akaike's information criterion (AIC) for the entire pandemic was computed. The best model was selected as having the lowest AIC and residuals that conformed to the parametric distribution. The predictor in the final model was a log-transformed value of GNI per capita.

Daily probability of infection

The daily probability of infection among susceptible individuals in country *c* who have not successfully developed immunity due to vaccination or infection is a product of new reported cases during that day, $\mathrm{NewCases}_{c,d}$, the underreporting correction factor, CF, and the inverse of the susceptible population (i.e. population that is not protected against infection due to vaccination and/or previous infection, using the country population size for 2020, $\mathrm{Pop}_{c,2020}$, see Eq.1 and Eq.2):

$$\beta_{c,d} = \frac{NewCases_{c,d} * CF}{Pop_{c,2020} * \left(1 - Pprotected_{c,d}\right) * (1 - Vacc_{c,d})} \quad (4)$$

From here onwards, the time varying underreporting correction factor is considered when calculating the population previously infected, $Pprotected_{c,d}$.

Note that for land importation risk, $\beta_{c,d}$ is calculated at the US state level using state level COVID-19 surveillance data.

Analyses

The model estimates the number of infected *CNDs* and *FTs* coming to Canada for a given week, *w*. For the following analyses, it is assumed that day 0 is the start of the pandemic and that day *s* is the day at which the individual travels from country *c* to Canada (i.e. *s* is the number of days between the start of the pandemic and the travel date to Canada). All events (travel to Canada, arrival in country *c*, PCR testing) are assumed to take place at the start of the given day. The latent and infectious periods are described by the normal distributions N(3.5, 1.0) and N(12, 4.0) days, respectively [22-24]. The sum of the latent and infectious periods is represented by the parameter *n* in the equations below.

Exempt travellers (pre-arrival test not required)

CND infection probabilities

It is assumed that a CND that has developed immunity following vaccination or has been infected (and remains immune to reinfection) in Canada prior to the date of departure from Canada to country *c* cannot import infection from country *c*.

When $t_c \leq n$, the probability of a CND importing infection from country *c* into Canada on day *s* is equal to the probability of that person getting infected on any day during the trip, multiplied by the probability of not having been infected in Canada prior to the trip and successfully acquiring protection against reinfection and not having been successfully vaccinated in Canada:

$$P_{c,s}^{E,CND,t_c-} = \left(1 - \prod_{d=s-t_c}^{s-1} \left(1-\beta_{c,d}\right)\right) \times \left(1 - Pprotected_{h,s-(t_c+1)}\right) \times \left(1 - Vacc_{h,s-(t_c+1)}\right) \quad (5)$$

When $t_c > n$, the probability of a CND importing infection from country *c* into Canada on day *s* is equal to the sum of the probability of not getting infected during t_c and the probability of getting infected in the country, recovering and becoming immune before departure multiplied by the probability of not having been infected in Canada prior to the trip and successfully acquiring protection against reinfection and not having been successfully vaccinated in Canada:

$$P_{c,s}^{E,CND,t_c+} = \left(\prod_{d=s-t_c}^{s-(n+1)} \left(1-\beta_{c,d}\right) - \prod_{d=s-t_c}^{s-1} \left(1-\beta_{c,d}\right)\right) \times \left(1 - Pprotected_{h,s-(t_c+1)}\right) \times \left(1 - Vacc_{h,s-(t_c+1)}\right) \quad (6)$$

FT infection probabilities

For FTs, when time in country *c* is larger than the sum of the latent and infectious periods (i.e. $t_c > n$), the probability of a traveller entering Canada infected is equal to the probability of getting infected on any day during the *n* days prior to travel to Canada, multiplied by the probability of not having been infected in country *c* prior to this *n*-day period and successfully acquiring protection against reinfection and the probability of not having been successfully vaccinated . For FTs, at this stage of the pandemic, the time spent in country *c* will always be greater than *n* (i.e. $t_c > n$). The probability of a FT travelling from country *c* to Canada on day *s* infected is therefore equal to:

$$P_{c,s}^{E,FT} = \left(1 - \prod_{d=s-n}^{s-1} \left(1-\beta_{c,d}\right)\right) \times \left(1 - Pprotected_{c,s-(n+1)}\right) \times \left(1 - Vacc_{c,s-(n+1)}\right) \quad (7)$$

Non-Exempt travellers (pre-arrival test required)

For a non-exempt traveller, infection is imported when a person travelling to Canada is infected on test day but has a false negative result or is not infected nor immune on test day but gets infected during the remaining days prior to departure. The probability of a non-exempt (NE) individual travelling by air from country *c* to arrive at their final destination in Canada on day *s* infected is equal to the sum of the probability of getting a false negative result on test day and the probability of getting infected on any day following the test given that the person was not infected and not immune on test day.

$$P_{c,s}^{NE} = P_{testday\_infect}^{NE} \times (1 - Se) + P_{testday\_no\_infect}^{NE} \times P_{infection\_after\_test}^{NE} \quad (8)$$

Where $P_{testday\_infect}$ is the probability of being infected on test day, $1 - Se$ is the probability of testing negative given infection on test day, $P_{testday\_no\_infect}$ is the probability of NOT being infected on test day for a person that is not immune through vaccination and has not been infected prior to the test and $P_{infection\_after\_test}$ is the probability of getting infected after the test day.

CND infection probabilities

It is assumed that a CND that has developed immunity following vaccination or has become infected (and remains immune to reinfection) in Canada prior to the date of departure from Canada to country *c* cannot import infection from country *c*. When the time in country *c* is smaller than or equal to the sum of the latent and infectious periods and the number of days between the PCR test and travel back to Canada (i.e. $t_c \leq n + \mu$), the probability of a CND being infected on test day is equal to the probability of getting infected at any given day within t_c before the test day multiplied by the probability of not having been infected in Canada prior to the trip and successfully acquiring protection against reinfection and not having been successfully vaccinated in Canada (similar to Eq. 5):

$$P_{testday\_infect}^{NE,CND,t_c-} = \left(1 - \prod_{d=s-t_c}^{s-(\mu+1)} (1 - \beta_{c,d})\right) \times \left(1 - Pprotected_{h,s-(t_c+1)}\right) \times \left(1 - Vacc_{h,s-(t_c+1)}\right) \quad (9)$$

The probability of NOT being infected on test day because the individual did not acquire infection on any day during the trip prior to the test, given that the person did not develop immunity through infection in Canada or vaccination is:

$$P_{testday\_no\_infect}^{NE,CND,t_c-} = \prod_{d=s-t_c}^{s-(\mu+1)} (1 - \beta_{c,d}) \times \left(1 - Pprotected_{h,s-(t_c+1)}\right) \times \left(1 - Vacc_{h,s-(t_c+1)}\right) \quad (10)$$

The probability of acquiring infection on any of the remaining days of the trip prior to departure to Canada is:

$$P_{infection\_after\_test}^{NE} = 1 - \prod_{d=s-\mu}^{s-1} (1 - \beta_{c,d}) \quad (11)$$

For CNDs, when $t_c \leq n + \mu$, based on Eq. 8, the probability of a CND importing infection from country *c* into Canada on day *s* is:

$$P_{c,s}^{NE,CND,t_c-} = \left[\left(1 - \prod_{d=s-t_c}^{s-(\mu+1)} (1 - \beta_{c,d})\right)(1 - Se) + \left(\prod_{d=s-t_c}^{s-(\mu+1)} (1 - \beta_{c,d})\right)\left(1 - \prod_{d=s-\mu}^{s-1} (1 - \beta_{c,d})\right)\right] \times \left[\left(1 - Pprotected_{h,s-(t_c+1)}\right) \times \left(1 - Vacc_{h,s-(t_c+1)}\right)\right]$$

$$\boldsymbol{P_{c,s}^{NE,CND,t_{c-}}} = \left[\mathbf{1} - \boldsymbol{Se} + \boldsymbol{Se}\prod_{\boldsymbol{d=s-t_c}}^{\boldsymbol{s-(\mu+1)}}\left(\mathbf{1}-\boldsymbol{\beta_{c,d}}\right) - \prod_{\boldsymbol{d=s-t_c}}^{\boldsymbol{s-1}}\left(\mathbf{1}-\boldsymbol{\beta_{c,d}}\right)\right] \times \left[\left(\mathbf{1}-\boldsymbol{Pprotected_{h,s-(t_c+1)}}\right)\times\left(\mathbf{1}-\boldsymbol{Vacc_{h,s-(t_c+1)}}\right)\right] \quad (\mathbf{12})$$

When time in country *c* becomes larger than the sum of latent and infectious periods and the number of days prior to testing (i.e. $t_c > n + \mu$), the probability of an individual being infected on test day is equal to the sum of the probability of not getting infected during t_c and the probability of getting infected in the country, recovering and becoming immune to reinfection before departure multiplied by the probability of not having been infected in Canada prior to the trip and successfully acquiring protection against reinfection and not having been successfully vaccinated (similar to Eq. 6):

$$P_{testday\_infect}^{NE,CND,t_{c+}} = \left(\prod_{d=s-t_c}^{s-(\mu+n+1)}\left(1-\beta_{c,d}\right) - \prod_{d=s-t_c}^{s-(\mu+1)}\left(1-\beta_{c,d}\right)\right)\times\left(\left(1-Pprotected_{h,s-(t_c+1)}\right)\times\left(1-Vacc_{h,s-(t_c+1)}\right)\right) \quad (13)$$

The probability of NOT being infected on test day because the individual did not acquire infection on any day during the trip prior to the test, and the person did not develop immunity through vaccination or infection in Canada is equal to Eq. 10:

$$P_{testday\_no\_infect}^{NE,CND,t_{c+}} = \left(\prod_{d=s-t_c}^{s-(\mu+1)}\left(1-\beta_{c,d}\right)\right)\times\left(\left(1-Pprotected_{h,s-(t_c+1)}\right)\times\left(1-Vacc_{h,s-(t_c+1)}\right)\right) \quad (14)$$

Therefore, based on Eq. 8, when the length of stay is longer, that is $t_c > n + \mu$, the probability of a CND importing infection from country *c* into Canada on day *s* is:

$$P_{c,s}^{NE,CND,t_{c+}} = \left[\left(\prod_{d=s-t_c}^{s-(\mu+n+1)}\left(1-\beta_{c,d}\right) - \prod_{d=s-t_c}^{s-(\mu+1)}\left(1-\beta_{c,d}\right)\right)(1-Se) + \left(\prod_{d=s-t_c}^{s-(\mu+1)}\left(1-\beta_{c,d}\right)\right)\left(1-\prod_{d=s-\mu}^{s-1}\left(1-\beta_{c,d}\right)\right)\right] \times \left[\left(1-Pprotected_{h,s-(t_c+1)}\right)\times\left(1-Vacc_{h,s-(t_c+1)}\right)\right]$$

$$\boldsymbol{P_{c,s}^{NE,CND,t_{c+}}} = \left[(\mathbf{1}-\boldsymbol{Se})\prod_{\boldsymbol{d=s-t_c}}^{\boldsymbol{s-(\mu+n+1)}}\left(\mathbf{1}-\boldsymbol{\beta_{c,d}}\right) + \boldsymbol{Se}\prod_{\boldsymbol{d=s-t_c}}^{\boldsymbol{s-(\mu+1)}}\left(\mathbf{1}-\boldsymbol{\beta_{c,d}}\right) - \prod_{\boldsymbol{d=s-t_c}}^{\boldsymbol{s-1}}\left(\mathbf{1}-\boldsymbol{\beta_{c,d}}\right)\right] \times \left[\left(\mathbf{1}-\boldsymbol{Pprotected_{h,s-(t_c+1)}}\right)\times\left(\mathbf{1}-\boldsymbol{Vacc_{h,s-(t_c+1)}}\right)\right] \quad (\mathbf{15})$$

FT infection probabilities

For FTs, at this stage of the pandemic, the time spent in country *c*, t_c, will always be greater than the sum of the latent and infectious periods and the number of days prior to testing (i.e. $t_c > n + \mu$). The probability of a FT being infected on test day is equal to the probability of acquiring infection on any day during the *n* days prior to the test, multiplied by the probability of not having been infected in country *c* prior to this *n*-day period and successfully acquiring protection against reinfection and the probability of not having been successfully vaccinated (similar to Eq. 7):

$$P_{testday\_infect}^{NE,FT} = \left(1 - \prod_{d=s-(n+\mu)}^{s-(\mu+1)} (1-\beta_{c,d})\right) \times \left((1 - Pprotected_{c,s-(n+\mu+1)}) \times (1 - Vacc_{c,s-(n+\mu+1)})\right) \quad (16)$$

The probability of NOT being infected on test day because the individual did not acquire infection on any of the *n* days prior to the test, and the person did not develop immunity through vaccination or infection in country *c* is:

$$P_{testday\_no\_infect}^{NE,FT} = \prod_{d=s-(n+\mu)}^{s-(\mu+1)} (1-\beta_{c,d}) \times \left((1 - Pprotected_{c,s-(n+\mu+1)}) \times (1 - Vacc_{c,s-(n+\mu+1)})\right) \quad (17)$$

Therefore, based on Eq. 8, the probability of a FT importing infection from country *c* into Canada on day *s* is:

$$P_{c,s}^{NE,FT} = \left[\left(1 - \prod_{d=s-(n+\mu)}^{s-(\mu+1)} (1-\beta_{c,d})\right)(1-Se) + \left(\prod_{d=s-(n+\mu)}^{s-(\mu+1)} (1-\beta_{c,d})\right)\left(1 - \prod_{d=s-\mu}^{s-1} (1-\beta_{c,d})\right)\right] \times \left[(1 - Protected_{c,s-(n+\mu+1)}) \times (1 - Vacc_{c,s-(n+\mu+1)})\right]$$

$$\boldsymbol{P_{c,s}^{NE,FT}} = \left[\mathbf{1} - \boldsymbol{Se} + \boldsymbol{Se} \prod_{\boldsymbol{d=s-(n+\mu)}}^{\boldsymbol{s-(\mu+1)}} (\mathbf{1}-\boldsymbol{\beta_{c,d}}) - \prod_{\boldsymbol{d=s-(n+\mu)}}^{\boldsymbol{s-1}} (\mathbf{1}-\boldsymbol{\beta_{c,d}})\right] \times \left[(\mathbf{1} - \boldsymbol{Pprotected_{c,s-(n+\mu+1)}}) \times (\mathbf{1} - \boldsymbol{Vacc_{c,s-(n+\mu+1)}})\right] \quad (18)$$

Calculating the number of passengers arriving infected in Canada

The mean number of travellers arriving infected in Canada on day *s* is:

$$I_s = \sum_{i,c,k} v_{c,i,k,s}^{NE}\left[qP_{c,s}^{NE,CND} + (1-q)P_{c,s}^{NE,FT}\right] + \sum_{i,c,k} v_{c,i,k,s}^{E}\left[qP_{c,s}^{E,CND} + (1-q)P_{c,s}^{E,FT}\right] \quad (19)$$

where $v_{c,i,k,s}^{NE}$ is the volume of passengers who require a pre-arrival PCR test, departing from country (or American state) *c*, point of departure *i,* on day *s,* and arriving in Canada at port of entry *k*. Similarly, $v_{i,k,s}^{E}$ is the volume of passengers for travellers that are exempt from pre-arrival testing. Also, *q* is the proportion of Canadians compared to the number of visitors departing from country (or American state) *c* to visit Canada. The model calculates the daily probabilities of introduction for CNDs and FTs departing from each country (or American state) at each of the seven days of a given epi-week. The daily number of travellers infected are calculated for each day and summed over the given epi-week.

Calculation of the number of infected passengers by variant

An infected passenger can only carry one variant. Data for variants of concern (VOC) and variants of interest (VOI) were downloaded from the GISAID EpiFlu™ Database [25] in accordance with the GISAID Access Agreement of data sharing terms (https://www.gisaid.org/registration/terms-of-use/). To estimate the number of passengers arriving with a VOC or VOI, it is assumed that the proportion of variants reported in the GISAID database, during a three-week period (which includes the week modelled and the two prior weeks), for the embarkation country (or American state) is in the same proportion that would be observed in infected travellers from these countries arriving in Canada. There are inherent biases within this assumption such as: 1) there can be targeting of samples to sequence towards people who have recently travelled internationally and recently had close contact with someone returning from international travel, 2) the number of samples sequenced may be insufficient to represent the current national profile of variants, which is why output for this report are restricted to countries

with at least 20 sequenced samples (Table A-2). It is difficult to account for biases from targeted sampling because the GISAID database does not systematically contain information for travel history and exposure location. To provide a wider perspective of variants that are circulating in the country samples from non-human hosts (*Felis catus, Canis lupus familiaris, Gorilla Gorilla Gorilla, Panthera leo, Mink, Chlorocebus sabaeus, Mus musculus, Panthera tigris jacksoni*) and from environmental sources (wastewater from domestic sewage) were also included.

Model assumptions

- Canadians and visitors to Canada experience the same rates of exposure (i.e. $\beta_{c,d}$) while in the departure country or American state.
- Infected travellers do not spread infection during travel.
- Susceptible travellers do not get exposed to COVID-19 during travel by non-travellers (e.g. airport service employees).
- The vaccine efficacy does not wane.
- Travellers are assumed to visit (or reside) in one country or American state before visiting Canada. This location is defined by embarkation location data for CNDs and FTs provided by CBSA.
- The Omicron variant is assumed to be the dominant variant globally from December 1, 2021 onwards.
- Infections with the Omicron variant will provide complete immunity against re-infection.
- Infections with a non-Omicron variant will provide complete immunity against re-infection with a non-Omicron variant, and 35% protection against infection with Omicron.

Model limitations

- The model does not account for the right-truncation of reported cases, i.e. there is underreporting in the most recent days because of infected people that yet to develop symptoms and seek testing.
- It is assumed that a person that is infected on test day with a negative result will automatically import the infection into Canada, regardless of their stage of infection.
- Given the underestimation of global case counts (resulting from the increased transmissibility of the Omicron variant), the model may underestimate the true number of imported cases.
- Uncertainty in the size of the immune population (due to previous infections with Omicron) may result in an overestimation of the number of imported cases.

Table A-2. Countries and the number of samples sequenced, *n*, from March 13 to 19, 2022 as reported in GISAID. Countries with a sample size less than 20 are not considered for model estimates of variants expected to arrive in Canada.

Country	n	Country	n	Country	n
United Kingdom	162,083	Brazil	1,001	Ireland	131
USA	38,383	Mexico	901	South Korea	128
Denmark	36,297	Slovakia	820	Costa Rica	114
Germany	11,964	Portugal	775	Brunei Darussalam	108
France	6,229	Japan	711	Sri Lanka	97
Austria	5,222	Singapore	656	Hong Kong SAR China	75
Sweden	4,385	Lithuania	633	Ecuador	63
Switzerland	4,008	Greece	561	Botswana	60
Belgium	3,322	Indonesia	474	Bangladesh	42
Italy	2,662	New Zealand	474	Republic of Moldova	40
Netherlands	2,579	Thailand	400	Sint Maarten	35
Canada	2,539	Chile	339	Argentina	34
Poland	2,523	Vietnam	291	Martinique	30
Australia	2,455	Malaysia	269	Curacao	29
Czech Republic	1,664	Cambodia	252	Trinidad and Tobago	24
Spain	1,481	Romania	224	Maldives	23
India	1,398	Croatia	205	Reunion	22
Israel	1,289	Finland	197	Philippines	21
Norway	1,072	District of Columbia	184	*	<20
Turkey	1,018	South Africa	155		

*Countries with less than 20 sequenced sample submissions: Pacific, Pakistan, Russian Federation, Colombia, Guadeloupe, Myanmar, Islamic Republic of Iran, American Samoa, Palau, Nepal, Seychelles, Kenya, Liechtenstein, Bonaire, French Guiana, Montenegro, Saint Martin, Syria

References

1. Messenger, J.C., S. Lee, and D. McCann, *Working time around the world: Trends in working hours, laws, and policies in a global comparative perspective*. 2007: Routledge.
2. Hellou, M.M., et al., *Nucleic-acid-amplification tests from respiratory samples for the diagnosis of coronavirus infections: systematic review and meta-analysis.* Clinical Microbiology and Infection, 2020.
3. Jüni, P., et al., *Use of rapid antigen tests during the Omicron wave.* . Science Briefs of the Ontario COVID-19 Science Advisory Table., 2022. **3**(56).
4. Voysey, M., et al., *Safety and efficacy of the ChAdOx1 nCoV-19 vaccine (AZD1222) against SARS-CoV-2: an interim analysis of four randomised controlled trials in Brazil, South Africa, and the UK.* The Lancet, 2021. **397**(10269): p. 99-111.
5. Omrani, A.S. and I.M. Tleyjeh, *Which are the best coronavirus disease 2019 vaccines?* Clinical Microbiology and Infection, 2021.

6. Lopez Bernal, J., et al., *Effectiveness of Covid-19 vaccines against the B. 1.617. 2 (Delta) variant.* N Engl J Med, 2021: p. 585-594.
7. Sharma, K., et al., *Vaccines for COVID-19: where do we stand in 2021?* Paediatric Respiratory Reviews, 2021.
8. Khoury, D.S., et al., *A meta-analysis of Early Results to predict Vaccine efficacy against Omicron.* medRxiv preprint, 2021.
9. Bar-On, Y.M., et al., *Protection of BNT162b2 Vaccine Booster against Covid-19 in Israel.* N Engl J Med, 2021. **385**(15): p. 1393-1400.
10. Pouwels, K.B., et al., *Effect of Delta variant on viral burden and vaccine effectiveness against new SARS-CoV-2 infections in the UK.* Nature Medicine, 2021: p. 1-9.
11. UK Health Security Agency, *SARS-CoV-2 variants of concern and variants under investigation in England; Technical briefing: Update on hospitalisation and vaccine effectiveness for Omicron VOC-21NOV-01 (B.1.1.529)*. 2021.
12. Ritchie, H., et al., *Coronavirus pandemic (COVID-19).* Our World in Data, 2020.
13. Wu, S.L., et al., *Substantial underestimation of SARS-CoV-2 infection in the United States.* Nature communications, 2020. **11**(1): p. 1-10.
14. Control, C.f.D. and Prevention. *COVID-19 Response. COVID-19 case surveillance public data access, summary, and limitations* 2021; Available from: *https://www.cdc.gov/coronavirus/2019-ncov/cases-updates/cases-in-us.html*:.
15. JHU. Available from: *https://coronavirus.jhu.edu/vaccines/us-states*.
16. Open COVID-19 Data Working Group. *Detailed Epidemiological Data from the COVID-19 Outbreak*. 2020; Available from: *http://virological.org/t/epidemiological-data-from-the-ncov-2019-outbreak-early-descriptions-from-publicly-available-data/337*. .
17. World Health Organization. *WHO COVID-19 detailed surveillance data dashboard*. Available from: *https://app.powerbi.com/view?r=eyJrIjoiYWRiZWVkNWUtNmM0Ni00MDAwLTljYWMtN2EwNTM3YjQzYmRmIiwidCI6ImY2MTBjMGI3LWJkMjQtNGIzOS04MTBiLTNkYzI4MGFmYjU5MCIsImMiOjh9*.
18. Dong, E., H. Du, and L. Gardner, *An interactive web-based dashboard to track COVID-19 in real time.* The Lancet infectious diseases, 2020. **20**(5): p. 533-534.
19. Census. *Table 2. RESIDENT POPULATION FOR THE 50 STATES, THE DISTRICT OF COLUMBIA, AND PUERTO RICO: 2020 CENSUS*. Available from: *https://www.census.gov/data/tables/2020/dec/2020-apportionment-data.html*.
20. ; Available from: *https://data.worldbank.org/indicator/SP.POP.TOTL?locations=TV*.
21. The World Bank. *GNI per capita, Atlas method (2019)*. 2019; Available from: *https://data.worldbank.org/indicator/NY.GNP.PCAP.CD*.
22. Cevik, M., C. Bamford, and A. Ho, *COVID-19 pandemic—a focused review for clinicians.* Clinical Microbiology and Infection, 2020. **26**(7): p. 842-847.
23. Weiss, A., M. Jellingsø, and M.O.A. Sommer, *Spatial and temporal dynamics of SARS-CoV-2 in COVID-19 patients: A systematic review and meta-analysis.* EBioMedicine, 2020. **58**: p. 102916.
24. Woodruff, A., et al., *COVID-19 infection: strategies on when to Discontinue isolation, a retrospective study.* American journal of infection control, 2020. **48**(9): p. 1032-1036.
25. Shu, Y. and J. McCauley, *GISAID: Global initiative on sharing all influenza data–from vision to reality.* Eurosurveillance, 2017. **22**(13): p. 30494.

5.2.4 Agent-based model

Note: The supplemental materials provided in this section are related to section 4.1 of this report.

Methods

The PHAC ABM has been previously published [1-3] and additional technical information can be found here:

- https://www.cmaj.ca/content/cmaj/suppl/2020/08/17/cmaj.200990.DC1/200990-res-1-at.pdf
- https://royalsocietypublishing.org/doi/suppl/10.1098/rsos.210233
- https://royalsocietypublishing.org/doi/10.1098/rsos.210834
- https://nccid.ca/phac-agent-based-model-on-covid-19/

The model is an age-stratified simulation model used to explore the transmission of SARS-CoV-2 in Canada. Based on the date of onset reported by the first domestic cases in Canada, it is assumed community transmission began on February 7, 2020 [4]. An outbreak is initiated with six symptomatic cases over a two-week period to propagate local transmission. Agents are modelled in ten distinct age groups accounting for differences in age-specific health outcomes and contact rates [5]. The model uses a daily time step over 1,424 days (day 0 representing February 7, 2020 to day 1,095 representing January 1, 2024).

Model environment and agent movement

Agents are assigned to a designated household and common environment (school, workplace or a mixed age meeting venue) according to their age using projections for Canada as a guide to assigning agents of age groups that are likely to come into contact with each other at home, at work, at school and in other locations; these other locations (e.g. restaurants, cafes, shopping centres, museums, libraries, movie theatres, grocery supermarkets, public parks, and beaches) are called mixed age venues [5]. Workplaces are defined by a more restrictive group of age groups mixing, primarily those in the 16 to 65 age group. Schools represent daycares, elementary and high schools with most agents in the 0 to 16 age group assigned to schools. Agents were distributed into the three common environments on weekdays. At model initialization, agents move between their household and common environment during the weekday spending on average of eight hours per day outside of home. Each weekend, a different group of agents are selected at random to visit a new mixed age environment than their regularly assigned one; and it is assumed schools and workplaces are closed on weekends. Mobility varied by age and between weekdays and weekends; it is assumed older agents were not as mobile during the weekdays as younger individuals but for simplicity, it is assumed weekend movement was uniform across age groups. Mobility was determined daily for each agent; agents could leave the household if selected by chance based on the probability estimated for their age group [1, 2].

Model framework

A framework of compartments was developed to represent epidemiological health states of agents (Figure A-1). All agents begin as susceptible (it is assumed the Canadian population is completely naïve to SARS-CoV-2) except for initially infected agents used to seed transmission. Infection occurs on successful contact between susceptible and infectious agents. Infectious agents occur as four states: asymptomatic, pre-symptomatic, mild symptomatic and severe symptomatic. Severe cases, after a pre-symptomatic period, are assumed to remain at home until hospitalisation and can only transmit infection to household members at a reduced rate of 50%. Whereas asymptomatic, pre-symptomatic and mild cases can infect both at home and in common environments. On infection, agents progress through different health states beginning with the exposed states (distinguished by

those exposed by a symptomatic case and those exposed by an asymptomatic case) until either recovery or death is reached. Recovered individuals remain immune from re-infection for the duration of the model run. The duration in which agents remain in each epidemiological health state varied between agents and was determined by sampling from probability distributions defined by the literature or Canadian data [1, 2]. In 2022, as a result of under-reporting during the Omicron wave, an under-reporting compartment was created in order to fit projected hospitalisation prevalence in the model to Canadian hospitalisation data [6].

Transmission of COVID-19 from infected agents to susceptible agents occur within the household and within common environments. For simplicity, the current model does not incorporate transmission during agent's commute or in other unique environments such as in hospitals or long-term care facilities. The model therefore represents the baseline number of infections, hospitalisations and deaths excluding isolated outbreaks such as those seen in long-term care facility, hospitals, and other localised outbreaks.

Vaccination

To simulate the impact of vaccination, the model includes three states representing the first, second and third dose (booster) administrations of vaccines (BuildingImmunity, BuildingImmunity2 and Booster) (Figure A-1). Agents can be infected via contact with an infectious agent during vaccination (i.e. while acquiring immunity after receiving the first and second doses) and post-vaccination (after the second dose, between the second and third dose and after third dose), with the protection acquired from the vaccine increasing each day from the first and second dose during a corresponding building immunity period, before waning immunity begins (Figure A-2). The receipt of a third dose (booster) during the waning immunity period resets the protection acquired from vaccines to the maximum protection afforded by the second dose (for wild-type, Alpha and Delta variants) or to a higher level (for Omicron variant). Susceptible agents that are vaccinated track the time since they received the vaccine doses and the resulting protective effects conferred.

Vaccination in the model is time-dependent and vaccine effectiveness (VE) against infection, clinical symptoms and severe health outcomes are modelled as follows:

1. The vaccine has a combination of effects, including prevention of infection, clinical symptoms, hospitalisations and death;
2. VE linearly increases with time from the first dose, with full immunity acquired 14 days after the first dose (Figure A-2);
3. Similarly, VE linearly increases with time from the second dose, with full immunity acquired seven days after the second dose (Figure A-2).
4. For agents with waning immunity, VE linearly declines with time during a waning immunity period (see *Assumption on waning immunity* below).
5. On receipt of a third (booster) dose during the waning immunity period, VE is automatically reset to full immunity acquired seven days after the second dose, i.e. the maximum protection (for wild-type, Alpha and Delta variants) or to a higher level (for Omicron variant) (Figure A-2, green bar).

Figure A-1. The PHAC agent-based model can explores vaccines against the wild-type and variants with unique characteristics in addition to other public health measures including case detection and isolation, contact tracing and quarantining, physical distancing and community closures.

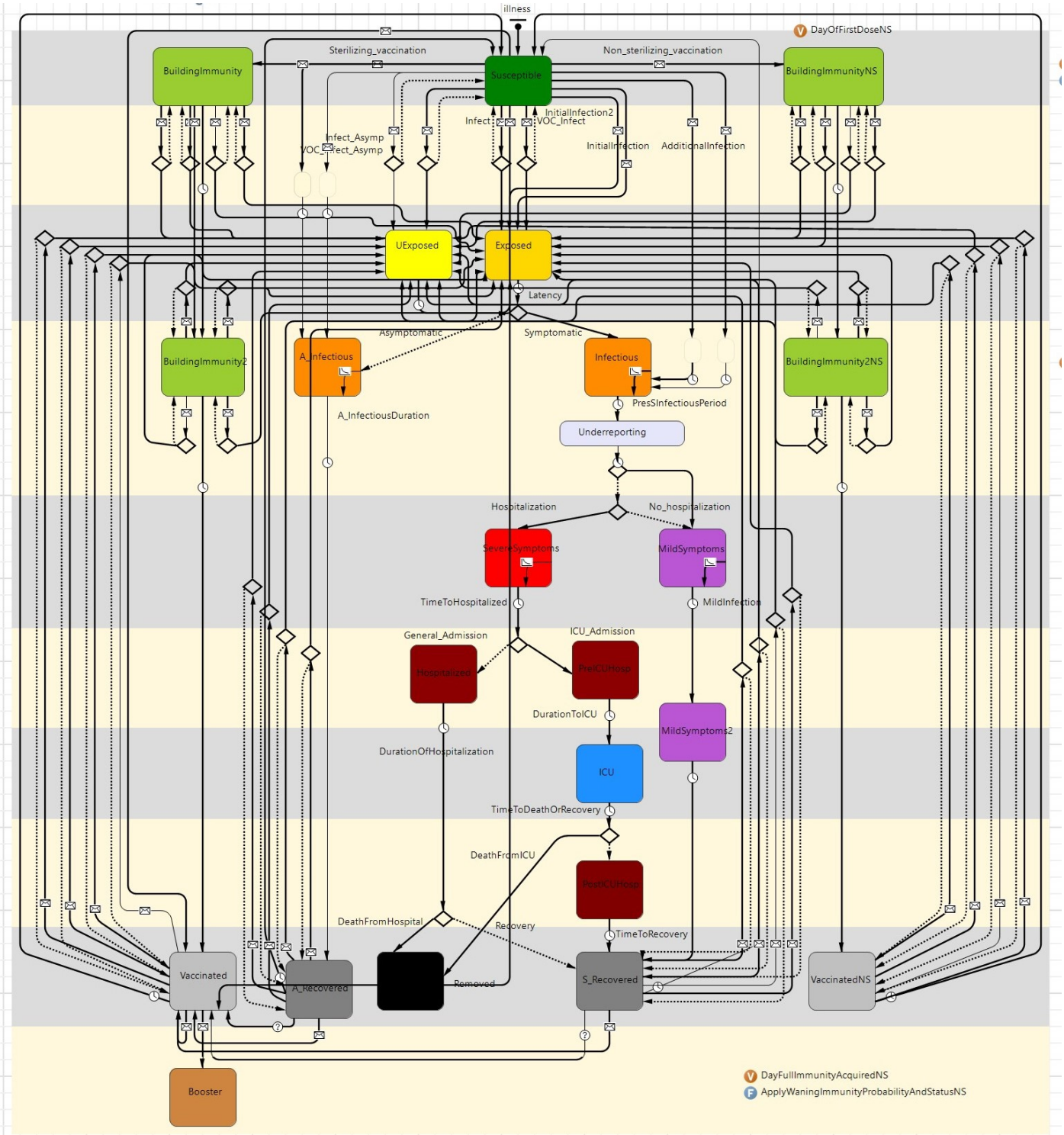
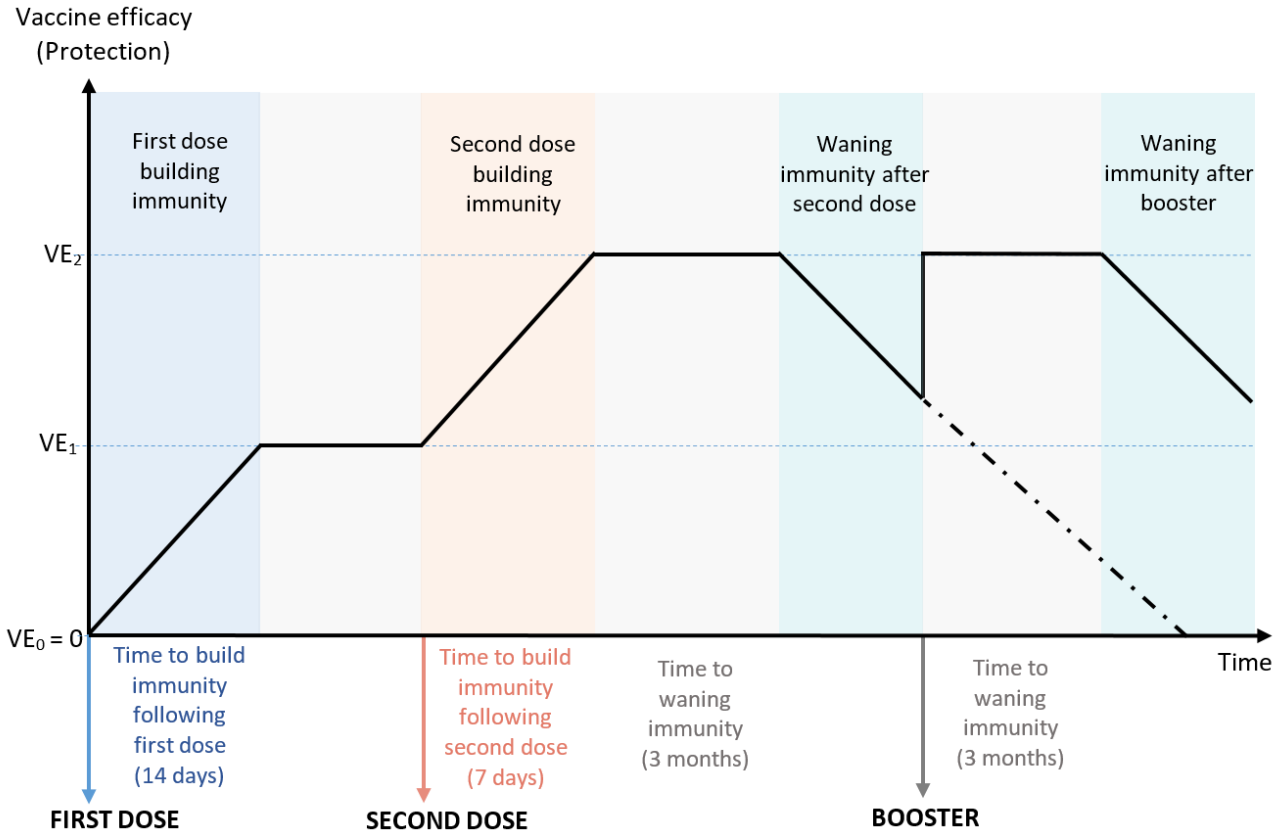


Figure A-2. The timing and acquisition of vaccine effectiveness against infection, clinical symptoms and severe outcomes after the first dose, second dose and booster (third dose). VE_1 and VE_2 corresponds to the maximal protection (vaccine effectiveness) against infection, symptoms, hospitalisations or death after dose one and after dose two, respectively. VE_0 is the protection prior to receiving any doses, which is equal to 0. The protection against infection and health outcomes increases over time after dose one and dose two administrations (Building immunity periods). Following a three month period in which immunity is retained following dose two and the booster, the protection decreases over time (Waning immunity period). This figure is not drawn according to scale.



Vaccine effectiveness

The model includes nested conditional probabilities for applying the impact of vaccines on protection against infection, clinical symptoms, hospitalisations and deaths. The overall VE against clinical symptoms, hospitalisations and death are adjusted as conditional VEs; that is, VE against symptoms given infection, VE against hospitalisations given symptoms and VE against death given hospitalisation. These conditional VEs were calculated as follows:

$$VE_{symp|inf} = 1 - \frac{(1 - VE_{symp})}{(1 - VE_{inf})} \quad (1)$$

$$VE_{hosp|symp} = 1 - \frac{(1 - VE_{hosp})}{(1 - VE_{symp})} \quad (2)$$

$$VE_{death|hosp} = 1 - \frac{(1 - VE_{death})}{(1 - VE_{hosp})} \quad (3)$$

Recommended and extended intervals between first and second doses

In the model, individuals receive two doses of vaccines and vaccination begins on December 14, 2020. The model accounts for the limited supply of vaccines in Canada between January and May 2021 and implements an extended interval between the first and second dose as of March 4, 2021; as recommended by NACI [7]. Individuals in the model vaccinated prior to March 4 receive a second dose of the vaccine 28 days after the first dose, while individuals vaccinated on or after March 4 receive a second dose only on or after May 25, 2021. At this point, first and second doses are administered simultaneously, with the proportion of first dose administration decreasing over time. First dose and second dose administration rates for ages 12 and over are based on data from Covid19 tracker, including data up to March 18, 2022 [8]. First and second dose administration rates for children age 5 to 11 are based on data from the Canadian Immunization Committee report dated March 18, 2022 including data up to and including March 13, 2022 [9]. In the latest update (modelling report dated March 24, 2022), the anticipated vaccination rollout end date ranges from March 2022 in the scenarios in which 55% of the eligible population receives a booster using the current rate to January 2023 in the scenarios in which boosters are administered using the current rate with delayed boosters in fall (Figure A-3, Table 5).

Booster dose

Booster doses are administered commencing September 17, 2021 using data from Covid19tracker.ca [8]. Weekly rates from September 17 to March 18, 2022 are based on real life data whereas rates from March 19, 2022 onward are projected to be maintained at 225 booster doses per 100,000 per day (current rate scenarios) or increased up to 1,392 doses per 100,000 per day (expedited rate scenario); the expedited rate represents a 32-fold increase of the current booster administration rate which is also the peak vaccine administration rate reported in the summer of 2021 [8]. The booster rollout end date ranges from March 10, 2022 to January 3, 2023 depending on the scenario (Table 5).

Imported cases

Where possible, the number of infected travellers entering the ABM population were estimated from the PHAC importation risk model. These numbers represent the number of infected travellers who either entered Canada after being tested at least 72 hours prior to travelling to Canada (pre-departure testing) and are assumed to have evaded detection or are exempt from testing [10, 11]. For the entire model run, the weekly number of imported cases per 100,000 in the ABM were broken down to one permanent case (staying in the population indefinitely) with remaining cases set as transient cases (staying in the population for one to five days). Permanent cases leading to hospitalisations were captured in the model outputs whereas transient cases leading to hospitalisations are not captured in the model outputs.

From the beginning of the pandemic to July 10, 2021, the number of infected travellers entering Canada was assumed to remain constant at two cases per 100,000 per week representing a closed border. From July 11, 2021 to February 26, 2022, the number of imported cases generated by the importation risk model for each week were extracted. Due to an underestimation of the importation risk model during the Omicron wave, the model estimates were corrected based on border testing data for the months of January and February 2022. Linear interpolation was used to estimate the number of imported cases throughout the month of December due to a lack of reliable data from the model. The counts from the importation risk model were adjusted to match the

population size for the ABM resulting in 293 imported cases per week entering a Canadian population of 100,000 during the peak of the Omicron wave (winter 2022). Subsequently, it was assumed that the number of imported cases remained constant at 5 cases per week per 100,000 from February 27, 2022 to the end of the model run. Figure A-4 shows the number of imported cases introduced into the models for this modelling report.

Figure A-3. Cumulative number of individuals vaccinated with the first dose (left column), the second dose (middle column) and the booster (right column) by age group for the four scenarios presented in the March 24, 2022 report.

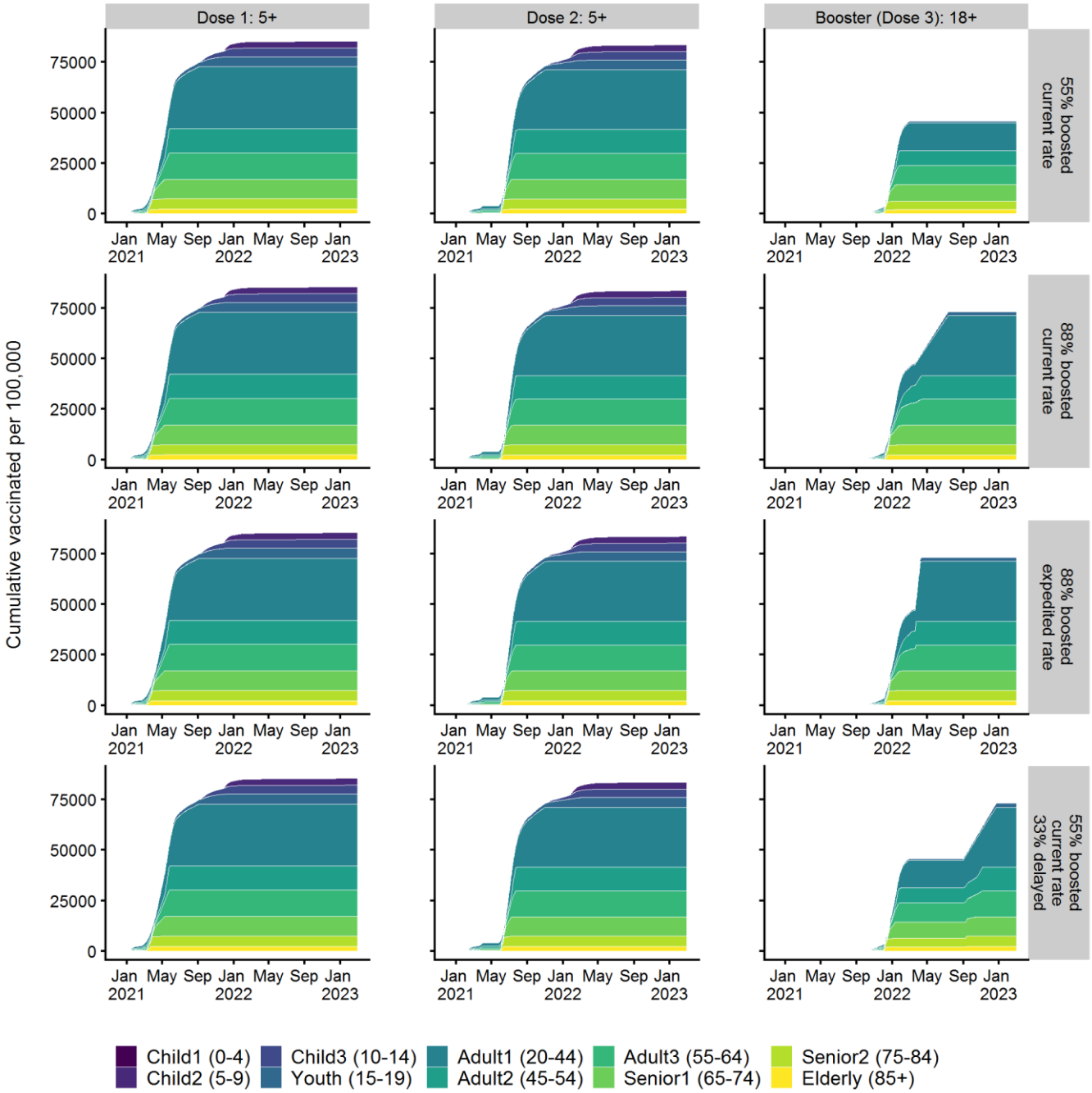
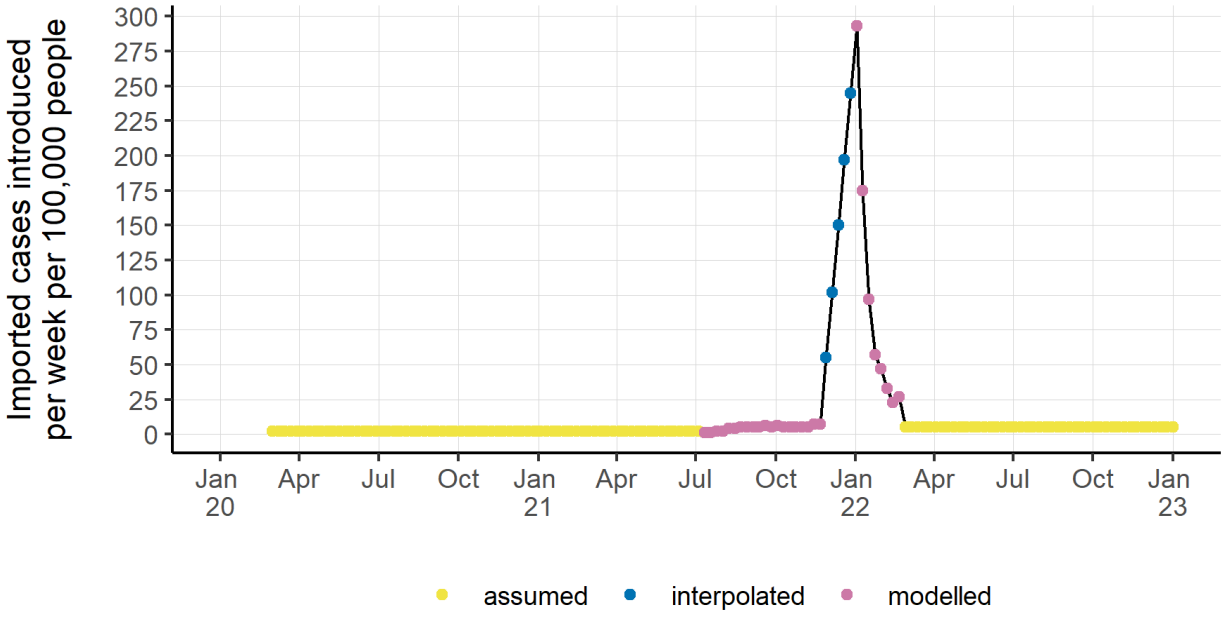


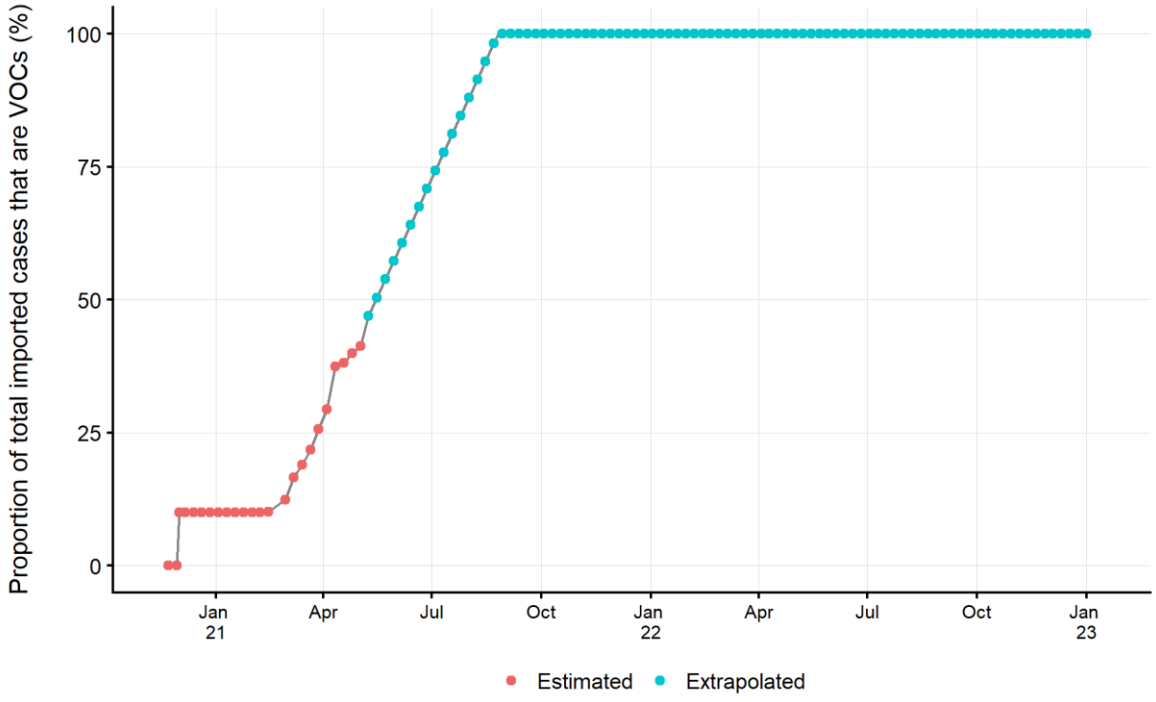
Figure A-4. Imported cases introduced into the ABM per week over time. Beginning March 1, 2020, two cases are imported each week per 100,000 people. From July 11, 2021 to February 26, 2022, the ABM imported cases are based on weekly estimates of the PHAC importation risk model, with linearly interpolated estimates during the month of December 2021. The number of imported cases remains at 5 per 100,000 people for the remainder of the model time.



Variants of Concern

The introduction of variants of concern (VOCs) occurs via imported returning travellers. When a susceptible agent is infected, they keep track of the infecting strain (VOC vs. wild type) and the probability of onward infection to other agents is dependent on the type of strain they have acquired. The model can explore two or more VOCs with different characteristics (i.e. transmissibility, virulence, immune escape from protection against infections, hospitalisations and deaths acquired from vaccines) in addition to the original wild-type strain. Figure A-5 shows the proportion of VOC entering the model population as an imported case. The values from December 2020 to May 9, 2021 are estimated from the PHAC importation risk model (red markers) and the subsequent data points (blue markers) are linearly extrapolated with the proportion of imported cases projected to be VOCs reaching 100% by August 29, 2021. The introduction of the Omicron VOC occurs on November 20, 2021, see the main report for additional information on the rate of introduction between Omicron and delta.

Figure A-5. Proportion of imported cases that are variants of concern as estimated by the PHAC importation risk model. The red markers indicate proportions estimated from model outputs, the blue markers indicate extrapolated data points estimated for future time periods. The proportion of imported cases that represent a VOC reaches 100% by August 29, 2021.



Model baseline (last calibrated in March 2022)

The current Canadian baseline scenario (Figure A-6) takes into account of historical public health measures that have been implemented and has been calibrated and fitted against hospital prevalence data at the national level [6]. Model assumptions are based on data where available and are summarised below:

Assumptions on case detection and isolation:

- 20% of cases are detected and isolated for the entire model period except when cases reach 150 active cases per 100,000, when this occurs, case detection and isolation is halved (10%) representing the collapse of the surveillance system [12-14].

Assumptions on contact tracing and quarantine

- 50% of detected cases are contact traced and identified for quarantine. When cases reach 50 active cases per 100,000, contact tracing ceases for the entire model period due to over-stretching of tracing capacity [15, 16].

Assumptions on physical distancing:

- Physical distancing (i.e. daily rates each person contacts other people) varies over the course of the pandemic (and have been previously published [1, 2]) with varying compliance across age groups according to survey data [17-19]. Physical distancing accounts for many public health measures that would reduce effective contact between individuals, for example, masking, restrictions on gathering, reducing contact rates, etc. but these are not modelled explicitly.

- During shutdowns, it is assumed that approximately 90% of the population is compliant with physical distancing uniformly across age groups. In between shutdowns, compliance is reduced to approximately 65% of the population being compliant, and ranges from 50% in the under 20 years age groups to 90% in the 65 years and over age groups.
- Physical distancing is maintained at a level corresponding to the stringency index at the time of each wave, it is adjusted according to other public health measures in place (for example, vaccine mandate and shutdowns), it is assumed physical distancing is maintained at the same level for the duration of each shutdown but gradually increases after each shutdown and until the next shutdown begins.

Assumptions on restrictive closures:

- Closures have occurred regularly over the course of the epidemic in Canada and are modelled on the decline in mobility observed during corresponding time periods using Google mobility data and Statistics Canada's survey on Canadians working from home [20, 21]. Closures include 100% of schools, 50% workplaces and 50% mixed age venues corresponding to the decline in mobility observed by location [20, 21].
- In the ABM, closures are modelled on the stringency index and relative to other public health measures in place at the time (for example, vaccine mandates and physical distancing), the duration of closures ranges from 28 days to 56 days.
- When closures are implemented, they are effective immediately whereas reopening occurs gradually after each wave. The gradual reopening varies between waves in terms of the speed of reopening but is consistent in the types of reopening with 100% of schools reopening first, 80% of workplaces reopening gradually representing a portion of the workforce that continues to telework indefinitely and 100% of essential businesses reopening gradually.
- In the summers of 2020 and 2021, 65% of schools remain open representing summer camps and activities that would bring children together over the summer. On September 8, 2020 and September 7 2021, schools reopen back to 100% full capacity representing the start of the respective school years.
- From March 2022, no further closures occur.

Assumptions on imported cases:

- The importation rate representing a closed border is two imported cases per 100,000 per week [22]. From July 11, 2021 to February 26, 2022, the ABM imported cases are based on weekly estimates of the PHAC importation risk model, with linearly interpolated estimates during the month of December 2021. The number of imported cases per week remains at 5 per 100,000 people for the remainder of the model time.
- The weekly number of imported cases per 100,000 in the ABM were broken down to one permanent case with remaining cases set as transient cases (staying in the population for one to five days).
- Imported cases adhere to public health measures at the same level as the population but with border testing and monitoring, while in reality imported cases may adhere to public health measures at a higher level than the general population, i.e. quarantine, isolation, physical distancing (though the model estimates are derived from a model that accounts for cases that have evaded detection prior to entry into Canada).

Assumptions on SARS-CoV-2 wild-type and variants of concern

- From December 1, 2020 onward, there is a 10% probability that each imported case is a variant of concern (VOC) (estimate). The proportion of VOC imported cases changes dynamically over time using data points estimated from the PHAC importation risk model (see Figure A-5) [22].

- The VOC is modelled on the Alpha (B.1.1.7) variant, which is 50% more transmissible [23] and 40% more virulent causing hospitalisations than the wild-type [24], but is not characterised by immune escape. It is assumed that infection with Alpha will provide very high immunity to future exposures to Alpha infections but not complete immunity from re-infection.
- The baseline includes the introduction of the delta (B.1.617.2) variant which is introduced on March 9, 2021 and dominates by August 29, 2021, delta is characterised by immune escape on protection against infection and is 100% more transmissible and 80% more virulent than the wild-type (Table 4 of the ABM report). It is assumed that infection with Delta will provide very high immunity to future exposures to Delta infections but not complete immunity from re-infection.
- The Omicron (B.1.1.529) variant is introduced on November 20, 2021 and dominates by December 31, 2021. This variant is characterised by immune escape on protection against infection, symptoms and hospitalisations. Omicron and is assumed to be 250% more transmissible and 30% less virulent than the wild-type (Table 4 of the ABM report). Omicron infection is assumed to produce 75% less symptomatic infections compared to WT and the other variants, this reduction varies by age group (assumption). It is assumed that infection with Omicron will provide very high immunity to future exposures to Omicron infections but not complete immunity from re-infection.

Assumptions on vaccination and waning immunity

- There is a three month period in which immunity is retained before waning begins [25, 26].
- Following vaccination or natural infection, after a three month period, protection against SARS-CoV-2 infection, symptoms and hospitalisation declines linearly over time but protection against death persists and does not wane [26].
- The maximal protection against infection, symptoms, hospitalisation and death, the rate at which the protection declines during the waning period and the residual protection levels retained following waning immunity will vary depending on the SARS-CoV-02 strain (see Tables 3 and 4 of the ABM report).
- Infection-acquired immunity and second dose vaccine-acquired immunity wane within the same time period.
- Immunity following a third dose booster against wild-type, alpha and delta infections will wane over time at the same rate as waning following second dose administration. Immunity following a third dose booster against Omicron infections will wane at a faster rate than waning following second dose administration because protection against infection and hospitalisation for Omicron infections is slightly higher after a booster compared to a second dose (see Tables 3 and 4 of the ABM report).
- The linear decrease of protection in time is applied on the population-level protection (with conditional protections recalculated each day based on this decrease).

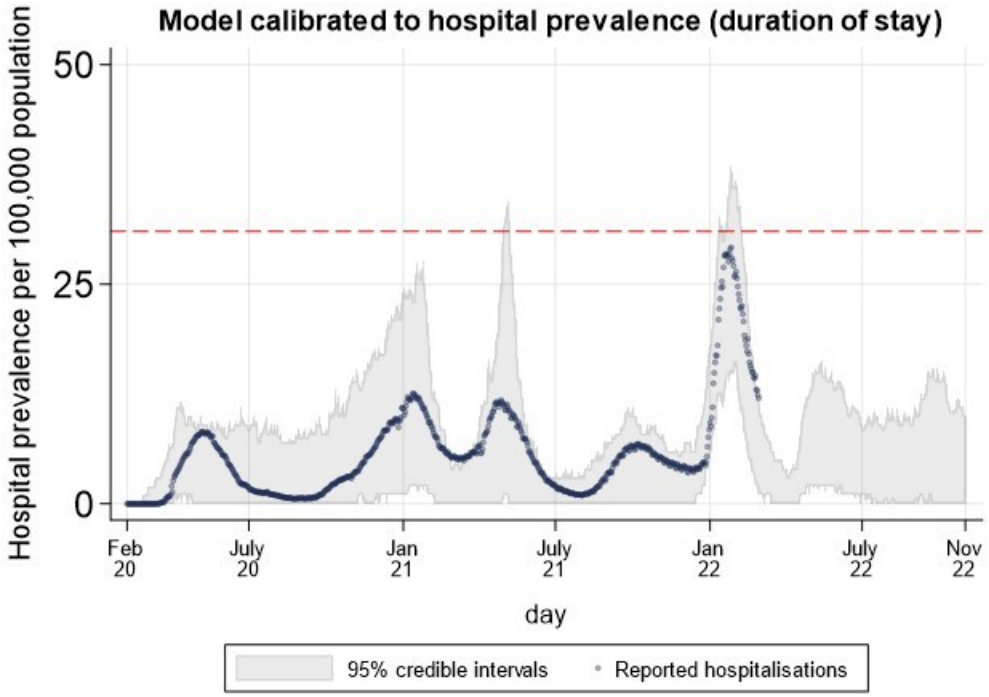
Assumptions on booster doses

- Boosters are administered in the same order of priority as the 1st and 2nd doses, in general, from the eldest to the youngest, the minimum age of boosting in the model is 18 years.
- Boosters are administered at a minimum of three months after the receipt of the 2nd dose.
- Booster weekly administration rates are estimated from covid19tracker.ca from September 17, 2021 to March 18, 2022 [8].
- Boosters are imperfect and provide protection against infection, symptoms, hospitalisations and deaths up to the level acquired by two doses of the vaccine (Table 3). For Omicron, the level of protection against infection and symptoms from the booster is higher than the two dose acquired immunity.
- On receipt of a booster dose, the time to waning immunity is reset providing another three month period in which immunity is retained before waning begins.
- Booster protection will vary depending on the variant and immune escape properties (see Tables 3 and 4 of the ABM report).

Assumptions on vaccine mandate:

- From September 15, 2021 to March 1, 2022, a vaccine mandate is introduced to the population restricting unvaccinated individuals from entering non-essential businesses (approximately 50% of mixed age venues). This represents what has happened across the provinces and territories with the lifting of a vaccine mandate in recent weeks (end of February to mid-March 2022).

Figure A-6. The baseline scenario. The blue markers represents hospital prevalence over time up to February 28, 2022. The shaded grey area represents the 95% credible interval of hospital prevalence from 200 model realizations from February 7, 2021 to November 3, 2022. This baseline includes the vaccination rollout and all public health measures implemented to date as well as projected measures according to the model scenarios presented in this report.



References

1. Ng, V., et al., *Projected effects of nonpharmaceutical public health interventions to prevent resurgence of SARS-CoV-2 transmission in Canada.* Canadian Medical Association Journal, 2020. **192**(37): p. E1053.
2. Ng, V., et al., *Modelling the impact of shutdowns on resurging SARS-CoV-2 transmission in Canada.* Royal Society Open Science, 2021. **8**(5): p. 210233.
3. Gabriele-Rivet V, et al., *Modelling the impact of age-stratified public health measures on SARS-CoV-2 transmission in Canada. .* Royal Society Open Science, 2021. **8: 210834**.
4. Public Health Agency of Canada, *National line list of COVID-19 cases. Extracted June 6, 2020*. 2020.
5. Prem, K., A.R. Cook, and M. Jit, *Projecting social contact matrices in 152 countries using contact surveys and demographic data.* PLOS Computational Biology, 2017. **13**(9): p. e1005697.
6. Li, M. *COVID19-Canada hospital prevalence data*. 2022 [cited 2022 March 10, 2022]; Available from: *https://wzmli.github.io/COVID19-Canada/*.

7. Government of Canada. *NACI rapid response: Extended dose intervals for COVID-19 vaccines to optimize early vaccine rollout and population protection in Canada*. 2021 [cited 2021 March 4, 2021]; Available from: *https://www.canada.ca/en/public-health/services/immunization/national-advisory-committee-on-immunization-naci/rapid-response-extended-dose-intervals-covid-19-vaccines-early-rollout-population-protection.html*.
8. COVID-19 Tracker Canada. *COVID-19 Vaccination Tracker*. 2022 [cited 2022 January 8, 2022]; Available from: *https://covid19tracker.ca/vaccinationtracker.html*.
9. Canadian Immunization Committee (CIC), *COVID-19 vaccination coverage in Canada. Weekly report to the Canadian Immunization Committee (CIC), March 17, 2022 report. Data also available at https://health-infobase.canada.ca/covid-19/vaccination-coverage/*. 2022.
10. Government of Canada. *Driving to Canada: COVID-19 testing for travellers*. 2021 [cited 2021 June 1, 2021]; Available from: *https://travel.gc.ca/travel-covid/travel-restrictions/driving-canada-checklist/covid-19-testing-travellers-driving*.
11. Government of Canada. *Flying to Canada: COVID-19 testing for travellers*. 2021 [cited 2021 June 1, 2021]; Available from: *https://travel.gc.ca/travel-covid/travel-restrictions/flying-canada-checklist/covid-19-testing-travellers-coming-into-canada*.
12. Centre for Mathematical Modelling of Infectious Diseases (CMMID). *Using a delay-adjusted case fatality ratio to estimate under-reporting*. 2020 [cited 2020 April 19 2020]; Available from: *https://cmmid.github.io/topics/covid19/global_cfr_estimates.html*.
13. Dougherty, B.P., et al., *Exploring the percentage of COVID-19 cases reported in the community in Canada and associated case fatality ratios.* Infectious Disease Modelling, 2020: p. 10.1016/j.idm.2020.11.008.
14. Public Health Ontario, *Enhanced Epidemiological Summary: COVID-19 Case Fatality, Case Identification, and Attack Rates in Ontario*. 2020. p. 12.
15. Toronto Public Health, *Temporary Change in Contact Tracing. Dated: October 8, 2020.* 2020.
16. City of Toronto, *City of Toronto COVID-19 Summary. Accessed: November 19, 2020*. 2020.
17. Montreal Behavioural Medicine Centre. *iCARE Study (Internaional COVID-19 Awareness and Response Evlauation Study)*. 2020 [cited 2020 November 16, 2020]; Available from: *https://mbmc-cmcm.ca/covid19/research/stats/adherence/*.
18. Institut national de santé publique du Québec (INSPQ), *CONNECT: étude des contacts sociaux des Québécois*. 2020.
19. Brankston, G., et al., *Quantifying Contact Patterns in Response to COVID-19 Public Health Measures in Canada. (in preparation).* 2020.
20. Google Canada. *COVID-19 Community Mobility Report*. 2020 [cited 2020 December 23, 2020]; Available from: *https://www.gstatic.com/covid19/mobility/2020-05-09_CA_Mobility_Report_en.pdf*.
21. Statistics Canada (StatsCan). *Canadian Perspectives Survey Series 1: COVID-19 and working from home, 2020*. 2020 [cited 2020 April 16 2020]; Available from: *https://www150.statcan.gc.ca/n1/daily-quotidien/200417/dq200417a-eng.pdf*.
22. Public Health Agency of Canada, *Public Health Agency of Canada biweekly modelling report: Importation Risk by Air and Land. Internal modelling report.* 2021.
23. Volz, E., et al., *Transmission of SARS-CoV-2 Lineage B.1.1.7 in England: Insights from linking epidemiological and genetic data.* medRxiv, 2021: p. 2020.12.30.20249034.
24. Public Health Agency of Canada, *VOC in Canada Daily Update April 6, 2021. Internal document based on a scan of publicly available data*. 2021.
25. Levin, E.G., et al., *Waning Immune Humoral Response to BNT162b2 Covid-19 Vaccine over 6 Months.* New England Journal of Medicine, 2021.
26. Chemaitelly, H., et al., *Waning of BNT162b2 Vaccine Protection against SARS-CoV-2 Infection in Qatar.* New England Journal of Medicine, 2021.

5.2.5 SEIR compartment model

Note: The supplemental materials provided in this section are related to Section 4.2 of this report.

Methods

A vaccine-stratified version (v24) of the dynamic deterministic compartmental model was developed using the susceptible, exposed, infected, removed (SEIR) framework applied to the Canadian population as presented in [8]. Specific pathways have been included for vaccination status: unvaccinated, vaccinated with a single-dose vaccine, vaccinated with two doses and boosted (vaccinated with three or more doses). Additional compartments and pathways have also been introduced to simulate waning from natural and vaccine acquired immunity.

Transmission between individuals can occur within or between age groups and within and between vaccination states at rates influenced by the daily contact number which is based on the contact matrix projected for Canada [8] and is also assumed to be influenced by vaccination (vaccines reduce the probability of transmission, symptomatic infection, severe disease and death).

Model parameters were obtained from the literature (for contact rates, case detection rates, percentage of contacts traced and quarantined, transmission coefficient when people make contact, as well as the time delay until isolation of cases) and by fitting the model to surveillance data in Canada for cases, hospitalisations and deaths up to December 20, 2021. Due the nationally widespread interruption in testing of COVID cases in the general population, the model was calibrated on hospital incidence alone following December 20, 2021. In order to do so, hospitalisation rates used in the model by age were fixed to those observed during the first half of the Omicron wave (up to week of December 20) and contact rate parameters were then used to alter total infections in the general population (detected or not) to allow fitting of simulated daily hospitalisation incidence to observed hospitalisation data from December 20, 2021 onwards.

The calibration process includes a parameter representing the general national level of public health measures, based on a stringency index [6], which is modulated by an age-specific coefficient representing factors such as adherence to public health measures and the probability of infection upon contact. This age-specific coefficient was adjusted on an empirical basis, by age group, on case incidence and hospitalisation. In addition, a “seasonal coefficient” that reduces transmission during the warmer months of each year of simulation starting in spring on April 15 was also included. In all simulations, this coefficient was kept active until September 1 of each year. Although adjusted on an empirical basis, it could be argued that this corresponds to a transfer of a fraction of contacts between individuals from closed environments to more open, outdoor interactions. In support of this, a study from the University of Bonn suggests that seasonality may be responsible for reducing transmission by as much as 43% of cases [3]

The general conceptual model of the PHAC SEIR is presented in Figure A1. The upper part of the figure illustrates the flows between the different vaccine and immune status compartments while the lower part presents the details of the flows between reservoirs of different infection status compartments that occur in a similar manner for all states of immunity.

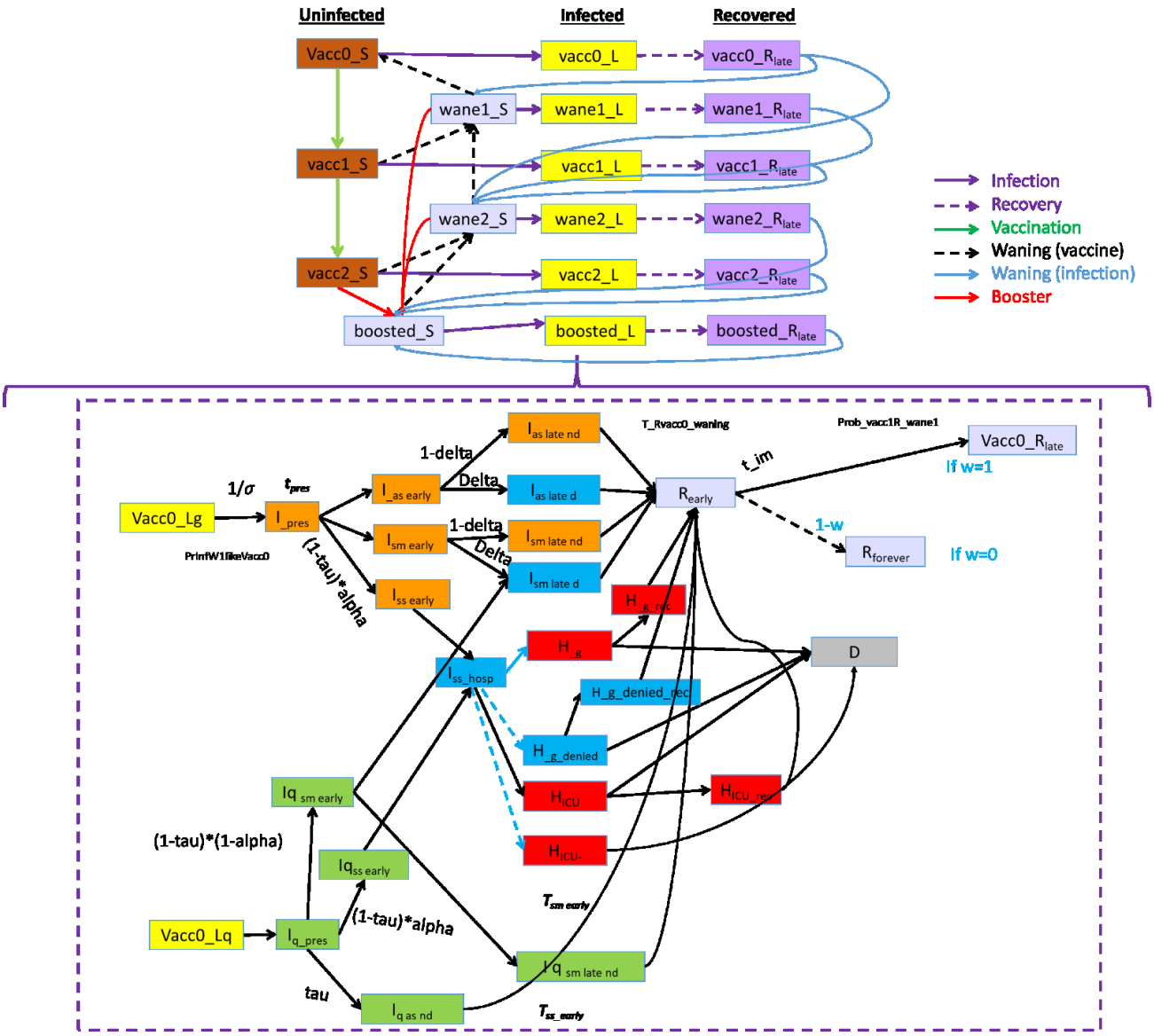


Figure A-1. Conceptual flow model of PHAC SEIR age stratified model v22.

Waning of immunity

Waning from both vaccine acquired immunity and infection acquired immunity can occur and is modelled using a discrete approach moving individuals in a stepwise fashion between compartments with different levels of protection against infection. A total of two intermediate compartments (wane1_S and wane2_S) are included in the model to account for the reduced effectiveness (i.e. waning) from a single and two doses of vaccination respectively. Specific transmission and disease protection values can be explicitly attributed for these waning compartments. Unless they get infected, individuals stay at the level of immunity attributed to the compartment for a predetermined period of time after which they are moved to the compartment with the next lower level of immunity. Individuals in "wane1_S" are eventually moved back to being completely susceptible. Recovered individuals that have not yet been vaccinated can transition to wane1 or wane2 with 80% transitioning to wane2 to approximately reflect the current level of vaccination in Canada.

A maximum amount of protection is assumed to be conferred after the booster dose of vaccination. The reduction of the level of protection associated with each of the wane compartments is defined in scenarios.

For a description of the speed and range of waning, see description of scenarios in the main body of the report.

Vaccination

Vaccination coverage is based on the current reported vaccine coverage in Canada [1]. The following vaccine rollout in five phases is used in the model:

- a period of 28 days between dose one and dose two from December 15, 2020 until the end of February 2021, after which;
- starting March 1, 2021, a 4-month interval was introduced between dose one and dose two until all dose one were completely administered, and finally; and
- a 28-day dose interval was reintroduced for the administration of the remaining second doses.
- 6-months following the administration of the second dose, booster doses are slowly rolled out for the small proportion of individuals that were vaccinated early with only a 28 day interval between their first and second doses.
- Starting in late November, booster doses begin to be slowly rolled out for the rest of the population (with older age groups prioritized for the first month) as this group began to reach their 6-month time mark since the administration of their second dose.

In all simulations, the maximum vaccination effect was implemented following a delay of 14 days for dose one and 7 days for doses two and three respectively.

Table A-1. Vaccine effectiveness (for Omicron variant, see the method section of the present report).

	Vaccine effectiveness		**Conditional effectiveness (model input)**	
	1 dose	**2 doses**	**1 dose**	**2 doses**
Against infection	60%	92%	60%	92%
Against symptoms	66%	94%	15%	25%
Against hospitalisation	80%	96%	41%	33%
Against death	85%	96%	25%	0%

Delta variant of concern

The Delta variant of concern was introduced into the model on March 1 2021, with a gradual dominance over all other strains over a six-month period. The Delta variant was introduced with a 50% increase in transmissibility over the Alpha strain (B.117). A reduction in vaccine efficacy was also incorporated for Delta with a value of 33 percent reduction after first dose and six percent after second dose. An increase in virulence of the Delta variant of 80% over wild type was also implemented.

Table A-2. Model compartment descriptions.

State	**Definitions**	**Initial values (blanks = zero)**
S	Susceptible	Stratification by age group, StatCan

		Population estimates July 1. 2019 [11] [0,10) 3,982,527 [10,20) 4,146,397 [20,40) 10,286,131 [40,60) 10,069,708 [60,75) 6,315,255 75+ 27,892,44
Svacc	Susceptible who are vaccinated	(is filled according to vaccine rollout)
Wane	Vaccinated or naturally infected recovered individuals that are subject to waning immunity (there is a Wane1 and a Wane2 compartment)	
Lq	Latent in quarantine	
L	Latent in the general population (not in quarantine)	10
I_pres	Infected pre-symptomatic in the general population (and first infectious period for asymptomatic)	20
Iq_pres	Infected pre-symptomatic in quarantine (and first infectious period for asymptomatic)	
Iq_as_nd	Infected in quarantine not detected (asympt) after the first phase of the infectious period until end of quarantine	
Iq_sm_early	Infected in quarantine with mild symptoms after the presymptomatic infectious period and before detection	
Iq_ss_early	Infected in quarantine with severe symptoms after the presymptomatic infectious period and before detection	
Iq_sm_late_nd	Non-detected Infected in quarantine with mild symptoms in the late phase of infectious period	
I_as_early	Infected non-detected in the general population with no symptoms between end of theoretical presymptomatic infectious period and detection	
I_sm_early	Infected non-detected in the general population with mild symptoms between end of presymptomatic infectious period and detection	
I_ss_early	Infected non-detected in the general population with severe symptoms between end of presymptomatic infectious period and detection	
I_as_late_nd	Infected in the general population that keeps being asymptomatic after possible detection time and are not detected	
I_as_late_d	Detected infected in the general population that keeps being asymptomatic after detection	
I_sm_late_nd	Infected in the general population that have mild symptoms and are not detected even after detection time	
I_sm_late_d	Detected infected in the general population that have mild symptoms	
Iss_hosp	Detected infected with severe symptoms, after early phase of infection, who are in hospital sorting	
H_g_OK	Infected with severe symptoms who stay at the hospital in the general care service during the first phase of hospital stay	
H_g_rec	Infected with severe symptoms who stay at the hospital in the general care service during the second phase of hospital stay	
H_ICU_OK	Infected with severe symptoms who stay at the hospital in ICU during the first phase of hospital stay	
H_ICU_rec	Infected with severe symptoms who stay at the hospital in ICU during the second phase of hospital stay	

H_g_denied	Infectious with severe symptoms who are not able to access hospital care because of insufficient/overwhelmed local capacity during the first phase of hospital stay	
H_g_denied_rec	Infectious with severe symptoms who are not able to access hospital care because of insufficient/overwhelmed local capacity during the second phase of hospital stay	
H_ICU_denied	Infectious with severe symptoms who are not able to access ICU because of insufficient/overwhelmed local capacity	
R_early	Recovered after infection	
R_forever	Recovered who keep been immune	
D	Dead	

Table A-3. Model parameter definitions and values.

Parameter	Definition	Value	References
beta	Probability of transmission when contact made with infectious person	Multiple values over time. Adjusted jointly with lambda and delta to best fit historical surveillance data up to Feb 15, 2021. Initial value for calibration process (0.052). After that date, values are based on scenarios (see Method section)	Public surveillance data online. https://health-infobase.canada.ca/covid-19/?stat=num&measure=total#a2 last accessed 2021-02-15 Initial value from [10].
beta_multiplier	Correction factor to account for the combined impact of increased transmission with variant or decreased transmission with vaccines		
lambda	Proportion of exposed to detected infectious who are traced and quarantined (contact tracing/quarantine)	Multiple values over time. Adjusted jointly with beta and delta to best fit historical surveillance data up to Feb 15, 2021. After that date, values are based on scenarios (see Method section)	Public surveillance data online. https://health-infobase.canada.ca/covid-19/?stat=num&measure=total#a2 last accessed 2021-02-15
cgg	Number of daily contacts between two individuals from the general population	6*6 matrix	Values available in [8]. Based on [9] and adapted to age-groups simulated.
cgq	Number of daily contacts between an individual from	6*6 matrix Based on the assumption that a person in	Values available in [8].

	the general population and an individual from the quarantined population	quarantine is in contact with a maximum of 1 person each day during his/her quarantine period. The value of one was then partitioned between age groups based on population size in each strata	
Cgg_multiplier	Parameter based on the stringency index [REF] to represent general public health measures over time		
Cgg_adjustor	Correction coefficient to account for non compliance to public health measures		
sigma	Latent period (days)	2.5 days. Calculated as the difference between incubation period duration and pre-symptomatic period duration.	
Delta	Adjusted jointly with Beta and Delta to best fit historical surveillance data	Multiple values over time. Adjusted jointly with lambda and beta to best fit historical surveillance data up to Feb 15, 2021. After that date, values are based on scenarios (see Method section)	Public surveillance data online. https://health-infobase.canada.ca/covid-19/?stat=num&measure=total#a2 last accessed 2021-02-15
Alpha	Proportion of symptomatic infected who develop severe symptoms.	[0,10) 0.52% [10,20) 0.55% [20,40) 1.07% [40,60) 3.07% [60,75) 10.02% 75+ 18.00% Calibrated to fit hospitalised data.	Hospitalised data: Public Health Agency of Canada. Preliminary dataset on confirmed cases of COVID-19. https://www150.statcan.gc.ca/n1/en/catalogue/13260003
tau	Proportion of infected individuals that are asymptomatic	31%	(1) (value for studies that identified SARS-CoV-2 infection through screening of defined populations).

$t_{\_pres}$	Period of time between onset of infectiousness and onset of symptoms in those developing symptoms	2.5 days	(2). Note, the authors indicate 2-3 days of pre-symptomatic infectious period (DFSO, days from symptoms onset) and chose to use the middle of those two values.
tsm_early	Period of time between onset of symptoms for mild cases or asymptomatic and detection	Values are based on scenarios (see Method section)	
t_{ss_early}	Period of time between onset of symptoms for severe cases or asymptomatic and detection	1 day	Based on the assumption that infected with severe symptoms (requiring hospitalisation) would seek out medical help within 1 day of symptoms onset.
t_{sm}	Total infectious period. Includes both pre-symptomatic and symptomatic infectious period	9.5	Symptomatic period (7 days) based on [12]. See "$t_{\_pres}$" parameter, upper in this table for the pre-symptomatic reference.
t_late_q_sm	Period of time between the possibility of been detected and end of quarantine for mild cases	Calculated assuming a quarantine duration of 14 days and using the values for t_pres (2.5 days) and the tsm_ealy values (see scenarios in method)	Assuming a quarantine duration of 14 days, based on the mandatory quarantine duration for travellers without symptoms returning to Canada. Source: Government of Canada, online rules, https://www.canada.ca/en/public-health/services/publications/diseases-conditions/2019-novel-coronavirus-information-sheet.html, consulted 2021-02-16
t_late_q_as	Period of time between end of theoretical presymptomatic infectious period and end of quarantine for asymptomatic	11.5 days Calculated assuming a quarantine duration of 14 days and a t_pres of 2.5 days.	Source: Government of Canada, online rules, https://www.canada.ca/en/public-health/services/publications/diseases-conditions/2019-novel-coronavirus-information-sheet.html, consulted 2021-02-16
p_{ICU}	Proportion of hospitalized cases who require/access to ICU in Hospital	----------	Although the model allows to partition hospitalised cases in general care and ICU, this functionality is not used for the moment.
$t_{sorting}$	Period of time for sorting severe cases in hospital	1 day	It is assumed it takes one day or less on average between when a severe case arrives in the hospital and when the case is sorted and isolated in the appropriate service.
m_g_early	Mortality rate for severe cases in hospital	[0,10) 0.79% [10,20) 0% [20,40) 1.59%	Hospitalised data: Public Health Agency of Canada. Domestic surveillance dataset on confirmed cases of COVID-19.

		[40,60) 5.63% [60,75) 16.22% 75+ 25.81%	Extraction Aug 2nd, 2021 – note: mortality are for all hospitalised (ICU and non ICU).
m_ICU_early	Mortality rate for severe cases dying in hospital (ICU)	----------	Partition hospitalised cases in general care and ICU, this functionality was not used for the moment. Instead, a global mortality rate for all hospitalised cases was used instead (see m_g_early).
t_hr_early	Period of time between first day in hospital after sorting, and death, for dead cases.	[0,10) 3 [10,20) 3 [20,40) 7 [40,60) 8 [60,75) 9 75+ 10	Based on [4], [7], [9].
th_late	Period of time between second period of hospitalisation, and recovery, for recovered cases.	1 day (the minimum without having to delete the compartment) Age-stratified	There are no clear solid evidence that the length of stay for survivor is longer than the length of stay for non-survivor.
m_g_denied	Specific mortality rate for severe cases dying at home because they are not able to access hospital care	Not used. This parameter was not used and mortality is not computed for scenarios for which hospital capacity is exceeded.	
m_{ICU-}	Specific mortality rate for severe cases dying in hospital because they are not able to access ICU	Not used. Mortality is not computed for scenarios for which hospital capacity is exceeded.	
ICU capacity		-----	Although the model allows to partition hospitalised cases in general care and ICU, this functionality was not used for the present simulations.
w	Percent of recovered who lose their immunity	0 or 1 for all age groups.	Set to 0 or 1 depending on inclusion of natural immunity waning or not in the simulations.
t_im	Duration of immunity for recovered	15 months	No clear evidence of waning of natural immunity, values of 15 months duration were tested in the present scenarios.

References

1. Buitrago-Garcia, D., D. Egli-Gany, et al. (2020). "Occurrence and transmission potential of asymptomatic and presymptomatic SARS-CoV-2 infections: A living systematic review and meta-analysis." PLOS Medicine 17(9): e1003346.
2. Chen, P. Z., N. Bobrovitz, et al. (2020). "Heterogeneity in transmissibility and shedding SARS-CoV-2 via droplets and aerosols." medRxiv: 2020.2010.2013.20212233.
3. Gablera, et al., 2021. “The effectiveness of Strategies to contain SARS-CoV-2: Testing, Vaccinations, and NPIs” ECONtribute Discussion Paper No.100. https://www.econtribute.de/RePEc/ajk/ajkdps/ECONtribute_100_2021.pdf
4. Gold, J. A. W., Wong, K. K., Szablewski, C. M., Patel, P. R., Rossow, J., da Silva, J., et al. (2020). Characteristics and clinical outcomes of adult patients hospitalized with COVID-19 - georgia, march 2020. MMWR Morb Mortal Wkly Rep, 69, 545-550. doi:10.15585/mmwr.mm6918e1.
5. Government of Canada, 2021. COVID-19 vaccination in Canada. https://health-infobase.canada.ca/covid-19/vaccination-coverage/#a4
6. Hale, T., Angrist, A., Goldszmidt, R., Kira, B., Petherick, A., Phillips, T., Webster, S., Cameron-Blake, E., Hallas, L., Majumdar, S., and Tatlow, H.. (2021). “A global panel database of pandemic policies (Oxford COVID-19 Government Response Tracker).” Nature Human Behaviour. https://doi.org/10.1038/s41562-021-01079-8
7. Kim, L., Whitaker, M., O'Halloran, A., Kambhampati, A., Chai, S. J., Reingold, A., et al. (2020). Hospitalization rates and characteristics of children aged <18 years hospitalized with laboratory-confirmed COVID-19 - COVID-NET, 14 states, march 1-july 25, 2020. MMWR Morb Mortal Wkly Rep, 69(32), 1081-1088. doi:10.15585/mmwr.mm6932e3.
8. Ludwig A, Berthiaume P, Orpana H, Nadeau C, Diasparra M, Barnes J, Hennessy D, Otten A, Ogden N. 2020 Assessing the impact of varying levels of case detection and contact tracing on COVID-19 transmission in Canada during lifting of restrictive closures using a dynamic compartmental model. Can Commun Dis Rep 46, 409–21
9. Prem, K., A. R. Cook, et al. (2017). "Projecting social contact matrices in 152 countries using contact surveys and demographic data." PLOS Computational Biology 13(9): e1005697.
10. Rizzo, S., Chawla, D., Zalocusky, K., Keebler, D., Chia, J., Lindsay, L., et al. (2020). Descriptive epidemiology of 16,780 hospitalized COVID-19 patients in the united states. MedRxiv, 2020.07.17.20156265. doi:10.1101/2020.07.17.20156265.
11. Sheng Li, Joseph N. S. Eisenberg, Ian H. Spicknall, James S. Koopman, Dynamics and Control of Infections Transmitted From Person to Person Through the Environment, American Journal of Epidemiology, Volume 170, Issue 2, 15 July 2009, Pages 257–265, https://doi.org/10.1093/aje/kwp116.
12. Statistics Canada. Estimates of population, by age group and sex for July 1, Canada, provinces and territories, annual (persons unless otherwise noted), CANSIM. Accessed 13 May 2020.
13. Wölfel, R. et al. Virological assessment of hospitalized patients with COVID-2019. Nature https://doi.org/10.1038/s41586-020-2196-x (2020).