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Note: This paper has not yet undergone formal peer review

Early intervention is the key to success in COVID-19 control

9 November 2020

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Executive Summary

- Evaluating the effectiveness of New Zealand's COVID-19 response, relative to counterfactual (alternative 'what-if') scenarios, is important for guiding future response strategies. We assess the importance of early implementation of interventions for controlling COVID-19.
- We model counterfactual scenarios in which the timings of three policy interventions are varied: border restrictions requiring 14-day quarantine of all international arrivals, border closure except to returning residents and citizens, and Alert Level 4 restrictions. We compare these to a modelled factual scenario in which intervention timings are the same as occurred in reality.
- Key measures describing the dynamics of a COVID-19 outbreak (notably peak load on the contact tracing system, the total number of reported COVID-19 cases and deaths, and the probability of elimination within a specified time frame), are used to compare outcomes between scenarios.
- Key measures were more sensitive to the timing of Alert Level 4, than to timing of border restrictions and border closure. Of the counterfactual scenarios, an earlier start to Alert Level 4 would have resulted in the greatest reduction in numbers of cases and deaths.
- Delaying the start of Alert Level 4 by 20 days could have led to over 11,500 cases and 200 deaths, and would have substantially reduced the probability of eliminating community transmission of COVID-19, requring a longer period at Alert Level 4 to achieve control.

Abstract

New Zealand responded to the COVID-19 pandemic with a combination of border restrictions and an Alert Level system that included strict stay-at-home orders. These interventions were successful in containing the outbreak and ultimately eliminating community transmission of COVID-19. The timing of interventions is crucial to their success. Delaying interventions for too long may both reduce their effectiveness and mean that they need to be maintained for a longer period of time. Here, we use a stochastic branching process model of COVID-19 transmission and control to simulate the epidemic trajectory in New Zealand and the effect of its interventions during its COVID-19 outbreak in March-April 2020. We use the model to calculate key measures, including the peak load on the contact tracing system, the total number of reported COVID-19 cases and deaths, and the probability of elimination within a specified time frame. We investigate the sensitivity of these measures to variations in the timing of the interventions. We find that a delay to the introduction of Alert Level 4 controls results in considerably worse outcomes. Changes in the timing of border measures have a smaller effect. We conclude that the rapid response in introducing stay-at-home orders was crucial in reducing the number of cases and deaths and increasing the probability of elimination.

Introduction

An outbreak of COVID-19, a novel zoonotic disease caused by the SARS-CoV-2 virus, was first detected in Wuhan, China in November 2019. The virus spread rapidly to other countries resulting in a pandemic being declared by the World Health Organisation in March 2020. Governmental policy responses to COVID-19 outbreaks have varied widely among countries, in terms of the nature and stringency of policy interventions, how quickly these interventions were implemented (Table 1) (Desvars-Larrive et al., 2020) and their effectiveness at reducing spread of the virus (Flaxman et al., 2020; Hsiang et al., 2020; Binny et al., 2020a). While it is tempting to judge the success of interventions by comparison across jurisdictions, this assessment may be confounded by local context that may influence success, as well as by the fact that policy choices can be driven by the severity of initial outbreaks. Models of disease spread played an important role in the design and timing of interventions, but they can also be used post hoc, to evaluate the effectiveness of those interventions. For example, Flaxman et al. (2020) and Brauner et al. (2020) fitted models of disease dynamics to case count and death data in different countries to estimate the effect of specific non-pharmaceutical interventions on the transmission rate of COVID-19.

In response to the escalating COVID-19 pandemic and the outbreak that was establishing in New Zealand in March 2020, a number of policy interventions were implemented to mitigate risk at the border and risk of community transmission. From 15 March 2020 (11.59pm), border restrictions were put in place requiring all international arrivals to 'self-isolate' (home quarantine) for 14 days. On 19 March 2020, the border was closed to everyone except returning citizens and residents. A system of four alert levels was introduced on 21 March with the Alert Level initially set at Level 2. On 23 March, it was announced that the Alert Level was increasing to Level 3, and that the country would move to Alert Level 4 as of 11.59pm on 25 March, signalling that NZ was taking a decisive COVID-19 response that would become known as an elimination strategy (Baker et al., 2020a). At the time Alert Level 4 came into effect, there had been 315 reported (confirmed and probable) cases. Alert Level 4 stayed in place until 27 April when restrictions were eased to Alert Level 3. On 13 May, after 16 days at Alert Level 3, daily new cases had dropped to 3 and there was a phased easing into Alert Level 2 (Table 2). The seven weeks spent under stringent Alert Level 3 or 4 restrictions, which included stay-at-home orders (see Appendix Table S3 for full list of measures) alongside systems for widespread testing, contact tracing and case isolation, were effective at reducing transmission (R_{eff} = 1.8 prior to Alert Level 4; R_{eff} = 0.35 during Alert Level 4; Binny et al., 2020b). Daily numbers of new cases declined to between zero and one by mid May and the last case of COVID-19 associated with the March outbreak was reported on 22 May. On 8 June, it was estimated that New Zealand had very probably eliminated community transmission of COVID-19 after 17 consecutive days with no new reported cases (Binny et al., 2020c). Between 22 May and 11 August, the only new cases detected were associated with international arrivals and during this period these arrivals were required to spend 14 days in government-managed isolation or quarantine facilities (Baker et al, 2020b). On 9 August 2020, New Zealand reached a milestone of 100 days with no community transmission.

Table 1: Timing of national border management and lockdowns in different countries (selected to illustrate the diversity of responses). Border restrictions describe 14-day quarantine restrictions in government-managed isolation and quarantine (MIQ) facilities, or at home, or in another country with little or no community transmission, unless otherwise stated. For most countries, earlier border restrictions were in place for travellers from certain high-risk/COVID-19-affected countries. Border closures are restrictions on the entry of specific categories of travellers (e.g non-citizens/residents, or potentially all arrivals). Lockdowns refer to physical distancing and movement restrictions which may extend to stay at home orders. Dates are given for the first occasion that measures were implemented along with Days after 1st reported case; Total cases refers to the number of cases at the time the measure was introduced. Note that some countries have since lifted and/or reinstated measures.

	Border restrictions			**Border closure**			**Lockdown**			**100 days after 1st case**	
Country/State /Province	**Date**	**Days after 1st case**	**Total cases**	**Date**	**Days after 1st case**	**Total cases**	**Date**	**Days after 1st case**	**Total cases**	**Cumulative cases**	**Cumulative deaths**
Samoa	15 Mar	No cases	0	20 Mar	No cases	0	26 Mar	No cases	0	0	0
Vanuatu	20 Mar	No cases	0	20 Mar	No cases	0	26 Mar[1,2]	No cases	0	0	0
Tonga	17 Mar	No cases	0	23 Mar	No cases	0	29 Mar	No cases	0	0	0
Solomon Islands	22 Mar	No cases	0	22 Mar	No cases	0	None	No cases	0	0	0
Fiji	20 Mar	1	1	25 Mar	6	5	20 Mar[1]	1	1	18	0
New Zealand	**15 Mar (Self-isol.); 9 Apr (MIQ)**	**18; 43**	**11; 1283**	**19 Mar**	**22**	**53**	**25 Mar**	**28**	**315**	**1504**	**22**
Vietnam	21 Mar	58	88	22 Mar	59	95	1 Apr	69	212	270	0
Taiwan	19 Mar	58	108	19 Mar	58	108	None	-	-	429	6
Iceland	18 Mar	19	247	20 Mar[3,4]	21	330	None[1,5]	-	-	1806	10
Australia	16 Mar	51	298	20 Mar	55	709	23 Mar[6]	58	1709	6801	95
Ontario, Canada	National: 25 Mar	60	688	National: 18 Mar	53	221	24 Mar	59	588	19,097	1446
South Africa	26 Mar[7]	21	709	26 Mar	21	709	26 Mar	21	709	61,927	1354
Japan	3 Apr	78	2617	1 Apr	76	1953	None[2]	-	-	12,892	551
Hubei, China	National: 28 Mar	132	67,801	Provincial: 23 Jan; National: 28 Mar	67; 132	444; 67,801	23 Jan	67	444	64,786	2563
Italy	17 Mar	46	27,980	17 Mar[3,4]	46	27,980	10 Mar	39	9172	218,268	30,395
Germany	10 Apr	74	113,525	18 Mar	51	7156	23 Mar	56	24,774	164,897	6996

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France	11 May	108	139,063	17 Mar	53	6633	17 Mar	53	6633	130,979	24,760
UK	8 Jun	131	264,039	None	-	-	23 Mar	54	8934	199,404	30,321
New York, USA	24 Jun[7]	115	389,666	None[8]	-	-	22 Mar	21	15,800	379,482	30,458
Sweden	None	-	-	19 Mar	44	1410	None	-	-	28,753	3745
Brazil	None	-	-	30 Mar	33	4256	None[1]	-	-	614,932	34,021

[1] *Local lockdown(s) only.*
[2] *Nationwide state of emergency declared ("soft" lockdown).*
[3] *Weak restrictions: travel permitted for work and health reasons.*
[4] *Border closed to all non-EU/EEA citizens.*
[5] *Highly intensive contact tracing and testing regime.*
[6] *Schools remained open in some states, though attendance dropped by up to 50% with many parents choosing to keep children at home.*
[7] *Restrictions apply only to travellers arriving from high-risk/COVID-19-affected countries/states.*
[8] *USA-Canada and USA-Mexico land borders closed to non-essential travel on 21 March and foreign nationals from certain COVID-19-affected countries not permitted to enter.*

Table 2: Dates of implementation for policy interventions during New Zealand's COVID-19 response. All interventions were implemented at 11.59pm.

Date implemented	Policy Intervention
15 March	14-day self-isolation (i.e. home quarantine) for all international arrivals
19 March	Border closed except to returning residents and citizens
21 March	Alert Level 2
23 March	Alert Level 3
25 March	Alert Level 4
9 April	Mandatory 14-day government-managed quarantine for all international arrivals
27 April	Alert Level 3
13 May	Alert Level 2 (schools and bars remain closed, gathering size limit 10)
18 May	Schools reopen
21 May	Bars reopen
25 May	Gathering size limit increased to 100
8 June	Alert Level 1: all restrictions lifted except border measures

A comparison of the outcomes of New Zealand's COVID-19 response interventions with predicted outcomes from hypothetical alternative actions is important for evaluating the effectiveness of the response choices made and to help refine future response strategies. In this work, we first model the factual scenario using New Zealand's actual intervention timings, then compare this to counterfactual (alternative 'what if') scenarios where policy interventions were implemented earlier or later than occurred in reality, to assess what impact this could have had for COVID-19 spread in New Zealand. For each scenario, we simulate a model of COVID-19 spread and compare key measures, including the peak load on the contact tracing system, the cumulative numbers of cases and deaths, and the probability of elimination predicted by the model.

In particular, we assess how important New Zealand's decision to move 'hard and early' was for the successful elimination of community transmission during the March-April outbreak. To this end, we compare scenarios with different timings until the start of Alert Level 4 to see how these choices could have affected the size of the outbreak. While Alert Level 4 was successful in achieving elimination, the benefits of elimination had to be weighed against the negative impacts of stringent stay-at-home measures, for example job losses, increased rates of domestic violence, disruption to education, and impacts on mental health. If careful border management could have avoided the need for a lockdown or reduced its intensity, this approach may have been preferable. For instance, Taiwan's early border closure, travel restrictions and 14-day quarantine for those entering the country have meant that, to date, Taiwan has avoided a mass lockdown (Summers et al., 2020). We explore whether introducing border restrictions (requiring 14-day self-isolation for all international arrivals) earlier in New Zealand might have been sufficient to eliminate or reduce transmission from international arrivals to the extent where stringent Alert Level 4 restrictions could have been avoided or less restrictive measures been sufficient. Compared to other countries, New Zealand was very quick to close its border to all except returning citizens and residents (Table 1). We explore a scenario where border closure is delayed by 5 days to assess how much larger the outbreak might have been had New Zealand been slower to act. We also consider a scenario where timings of two interventions are altered, to check whether this combination amplifies or counteracts the outcome trends found in scenarios where timings are varied for interventions individually. However we do not perform exhaustive comparisons of all possible combinations of different timings for all interventions. Finally, we consider a scenario with no Alert

Level 4/3 restrictions to compare the size of outbreak that New Zealand could have experienced if border restrictions and closure had been the only control measures.

In this study, we focus on the timing of interventions; we do not explicitly consider the duration of interventions, although this will be investigated in future work. Indeed, the likelihood of elimination was one of the factors taken into account in New Zealand government decision-making concerning the duration of Alert Levels (DPMC, 2020).

Methods

We simulated a stochastic model of COVID-19 spread in New Zealand (James et al., 2020a; Plank et al., 2020a) under a factual scenario using actual timings for border restrictions, border closure and Alert Level 4, and for counterfactual scenarios in which implementation of these interventions were either delayed or started earlier. Case data were obtained from ESR, containing arrival dates, symptom onset dates, isolation dates and reporting dates for all international cases arriving in New Zealand between February and June 2020. The model, described in full by Plank et al (2020a), is a continuous time branching process that is seeded with internationally imported cases and simulates the numbers of new clinical and subclinical cases that are acquired through local transmission each day. It accounts for delays from infection to symptom onset, and from symptom onset to date of reporting. We assume that the time between an individual becoming infected and infecting another individual (the generation time) follows a Weibull distribution, with a mean and median of 5 days and standard deviation of 1.9 days. The model incorporates individual heterogeneity in transmission rate (e.g. super-spreaders) and assumes that a proportion of clinical cases are undetected by testing and do not get reported, as described in James et al. (2020a). With the exception of heterogeneity in an individual's reproduction number, individuals are otherwise assumed to be homogenous and the population well mixed. The number of infections that result in death is calculated using an infection fatality rate (IFR) of 0.88%; this value was obtained by fitting age-specific COVID-19 IFR estimates from international studies (Verity et al, 2020) to the age distribution of the New Zealand population from 2018 Census data (Statistics New Zealand, 2020). We account for three classes of interventions for reducing onward transmission: (i) self-isolation (i.e. home quarantine), simulated as a reduction in an individual's infectiousness relative to their infectiousness when not isolated; (ii) government-managed isolation and quarantine (MIQ), which we assume is 100% effective at preventing onward transmission; (iii) population-wide control, modelled as a reduction in transmission rate relative to no population-wide control, due to restrictions under each of the four Alert Levels. The model assumes that subclinical cases are not reported and do not self-isolate. A list of model parameters used in simulations is provided in Table S1.

In each scenario, we kept the duration of each Alert Level (AL) the same as actually occurred, i.e. 33 days at AL4 followed by 16 days at AL3. We explored the following scenarios (see Table 2):

0. **Border restrictions, border closure and AL4 implemented on actual dates.**
1. **Early AL4.** Border restrictions and closure implemented on actual dates, and start of AL4 implemented 5 days early.
2. **Delayed AL4.** Border restrictions and closure implemented on actual dates, and start of AL4:
    a. delayed by 5 days,
    b. delayed by 10 days,
    c. delayed by 20 days.

3. **Early border restrictions.** Border restrictions 5 days earlier; border closure and AL4 on actual dates.
4. **Delayed border closure.** Border closure delayed by 5 days; border restrictions and AL4 on actual dates.
5. **Change in timing of AL4, border restrictions and closure**:
    a. Border restrictions 5 days early and AL4 5 days early; border closure on actual date.
    b. Border closure and AL4 delayed by 5 days; border restrictions on actual date.
6. **No AL4.** No AL3 or AL4 implemented; border restrictions and closure on actual dates.

Border restrictions, border closure and start of AL4 were all implemented at 11.59pm so we start simulating their effects on the day after their implementation date. For scenarios 0, 1, 2, 3 and 6, the model was seeded with the same number of international cases as were actually reported. In scenarios where border restrictions were implemented on the actual start date (15 March; Scenarios 0, 1, 2, 4 and 6), the self-isolation dates of international cases were set to the same isolation dates as were actually reported. In all scenarios, prior to 9 April the modelled effect of self-isolation is to reduce an individual's infectiousness to 65% of their infectiousness when not isolated. This reflects some risk of onward transmission for cases self-isolating at home. After 9 April, the model assumes that all international cases are placed in MIQ facilities and do not contribute to local transmission. We also simulated a Poisson-distributed random number of international subclinical cases in proportion to the number of international clinical cases (assuming 1/3 of all cases are subclinical), with arrival and symptom onset dates that were randomly sampled with replacement from the international case data. We assume that these international subclinical cases are not detected and therefore do not self-isolate, but those arriving after 9 April are placed in MIQ.

To simulate border restrictions starting 5 days early (Scenarios 3 and 5a), international cases arriving between the earlier start date and the actual start date (11 - 15 March, inclusive) were assumed to be self-isolated on their date of arrival. To simulate a 5-day delay to border closure (Scenarios 4 and 5b), we delayed the arrival dates (and associated symptom onset, reporting and isolation dates) of international seed cases arriving after 19 March by 5 days. We then allowed for new international cases arriving over these 5 days (e.g. additional non-residents that may have chosen to travel had the border remained open for longer) by seeding an additional Poisson-distributed random number of international cases from 20 March to 24 March, with an average daily number of seeded cases equal to the actual average daily number of international cases arriving during the week prior to 19 March (33 international cases per day). These additional seeded cases were assumed to self-isolate on arrival and their delays from arrival-to-symptom onset and arrival-to-reporting were randomly sampled with replacement from the corresponding delays in the actual international case data. We did not attempt to simulate scenarios with delayed border restrictions or earlier border closure because these would have required additional modelling assumptions about isolation dates of international arrivals and about the reduction in the volume of international arrivals resulting from border closure. Model predictions would have been highly sensitive to these assumptions and, without data available to validate them, this would introduce additional model uncertainty.

For each scenario, we assessed the following key measures describing the dynamics of a COVID-19 outbreak:

1. The maximum contact tracing (or health system) load, by calculating the maximum number of daily new reported cases and the date on which this occurred.
2. The number of daily new reported cases at the end of AL4.

3. Cumulative number of reported cases and the cumulative number of deaths at the end of the seven week period of Alert Level 3-4 restrictions (i.e. end of AL3).
4. Probability of elimination, *P(elim)*, 5 weeks after the end of AL3.

The first measure is useful for assessing whether the contact tracing or health system capacity would have been exceeded. The second measure indicates the daily incidence of cases after four weeks of the most stringent restrictions under AL4, and at the time when restrictions are eased to AL3 (e.g. schools, years 1 to 10, and Early Childhood Education centres can re-open with limited capacity, and non-essential businesses can re-open premises but cannot physically interact with customers; see Appendix Table S3). The third measure quantifies the overall health cost of the outbreak. Given New Zealand's elimination strategy (Baker et al., 2020a), we included the fourth measure to assess the likelihood of achieving elimination of community transmission under the different intervention timings. This is an important consideration because in scenarios resulting in low probabilities of elimination after AL3 restrictions are eased, there is a higher risk of cases persisting undetected in the community and sparking a new outbreak under the weaker AL2 restrictions. For example, gatherings of up to 100 people are permitted under AL2, increasing the risk of super-spreading events arising. If a new outbreak did occur then another lockdown may be required and the overall health cost would be even higher than that of our third key measure.

We performed 5000 realisations of the model and report the average value of each key measure as well as the interval range within which 90% of simulation results were contained (in square brackets throughout). Here, we define elimination as there being no active cases (we assume a case remains 'active' for 30 days after date of exposure) that could contribute to future community transmission. This definition excludes cases in MIQ, that is it excludes international arrivals after 9 April 2020. In the model, *P(elim)* was calculated as the proportion of all model realisations that resulted in elimination. Simulations were run using estimates of reproduction number R_{eff} that provided the best fit to actual data (Binny et al., 2020b): for the period prior to lockdown $R_{eff} = 1.8$; during Alert Level 4 $R_{eff} = 0.35$. Under the Alert Levels 3, 2 and 1, which followed the lockdown, the daily numbers of new cases were too low to obtain reliable estimates of the effective reproduction number R_{eff}. Instead we simulated the model for assumed values of $R_{eff} = 0.95$, 1.7 and 2.4, respectively. $R_{eff} = 2.4$ is in line with estimates reported in Plank et al (2020b) for the pre-lockdown period of New Zealand's August-September outbreak, when AL1 restrictions were in place. AL2's R_{eff} would likely be lower than AL1 but greater than one due to relatively high activity levels and contact rates as stay-at-home orders are lifted and public venues, businesses and schools re-open; $R_{eff} = 1.7$ is in the range of estimated values for the pre-lockdown period of the March-April outbreak given in Plank et al (2020b). The R_{eff} for AL3 was chosen to be less than 1, however we tested the sensitivity of our results to using a value greater than one. For the scenario with no stringent Alert Level restrictions (Scenario 6), we simulated the model using $R_{eff} = 1.8$ for the entire period (i.e. the same value as was used in all Scenarios for the period prior to AL4).

Sensitivity analyses

We investigated how varying the length of the delay (in days) until the start of AL4 (cf. the delays chosen in Scenario 2) affected key measures. Similarly, we assessed the effect on the key measures of introducing border restrictions 10 days early (cf. 5 days early in Scenario 3). James et al (2020a) tested the sensitivity of model results to variations in certain model parameters, including the proportion and relative infectiousness of subclinicals, the individual heterogeneity in transmission rate, and the mean generation time. Changes in parameters that resulted in a change in the overall population reproduction number, R_{eff}, caused a corresponding change in the outbreak trajectory. However, if R_{eff} was set to a fixed value the model was robust to changes in these parameters. Longer mean generation times reduce the overall population reproduction number R_{eff}, corresponding to slower spread of the virus. Increasing the individual heterogeneity in transmission rate increases the variation between independent realisations of the model and increases the probability of elimination (Lloyd-Smith et al, 2005). If higher proportions of clinical cases are detected and reported, this is associated with a reduction in overall population R_{eff} and higher estimates of probability of elimination (Binny et al, 2020c). Results are relatively insensitive to moderate changes in the rate of transmission relative to no population-wide control, *C(t)*, under each Alert Level (Binny et al, 2020c; James et al, 2020a). Binny et al (2020b) showed that the best-fit R_{eff} estimates for AL4 were relatively insensitive to changes in model parameters. Here, we tested the sensitivity of our results to different choices of relative transmission rate *C(t)* (corresponding to changes in R_{eff}) under AL3.

Results

Scenario 0

To check that the model could accurately replicate the outbreak, we first simulated our model under a factual scenario with border restrictions, border closure and AL4 implemented on the dates they actually occurred. The predicted dynamics of daily new reported cases were a very good visual match to observed daily case data (Fig. 1) and predicted key measures showed good agreement with the values that were actually observed (Table 3, bold text). After moving into AL4, the model prediction and the actual number of daily new reported cases both levelled off at 70-80 for around one week before case numbers started to decline (Fig. 1). In actual case data, the maximum of 84 new cases per day was observed at the start of this flat-topped peak, while our model predicted a similar maximum (80 [67, 99] new cases per day) occurring 6 days later. By the end of AL3, the model predicted similar cumulative totals to the 1502 cases and 21 deaths actually reported. Five weeks after AL3 restrictions were relaxed, elimination of community transmission of COVID-19 was achieved in 66% of model simulations, giving *P(elim)*=0.66 (Table 3). In the following counterfactual scenarios with alternative timings of interventions, we use Scenario 0 as a baseline for comparing key measures.

Scenario 1: Early AL4

Under a scenario where AL4 was implemented 5 days earlier (only one day after border closure), the model predicts slightly lower values for most key measures than were actually observed: daily new cases peaked at a lower level of 69 [61, 79] cases around 26 March and at the end of AL4 had dropped to a similar level of 4 new cases per day as was actually observed (Fig. 1). By the end of the 7 weeks of AL4/3 it predicts approximately 500 fewer cases in total and 10 fewer deaths (Table 3; Scenario 1 cf. Scenario 0). However, this estimate should be taken with caution because of the small numbers of daily cases and fine-scale variations involved: for instance, whether an outbreak occurred in an aged care facility or not. Five weeks after AL3, the probability of elimination was 63%, slightly lower than in Scenario 0. This counter-intuitive result is due to the presence of an international case in the data that had an arrival date prior to the start of AL4 (25 March) but a much later symptom onset date near the end of AL4. In Scenario 0, when international cases are seeded in the model, this individual's peak infectiousness occurs during AL4. However, in Scenario 1, the earlier start to AL4 means that the individual is instead most infectious during AL3. With a lower R_{eff} in AL3, this individual infects more people, on average, in this scenario than in Scenario 0. Similarly, any simulated subclinical cases with the same arrival and symptom onset dates (drawn from the international case data) will also be most

Table 3: Key measures from alternative scenarios of early or delayed implementation of policy interventions: the maximum number of daily new reported cases, date on which the peak occurs, the number of daily new cases at the end of the simulated Alert Level 4 period, the cumulative number of cases and the total number of deaths at the end of the simulated 7 week period of Alert Level 4/3 restrictions (dates given in 'AL3 ends' and footnotes), . For each measure, except P(elim), the mean value from 5000 simulations is reported alongside the interval range, in parentheses, in which 90% of simulations results are contained.

Scenario	**Border self-isolation**	**Border closed**	**AL4 starts**	**AL3 ends**	**Max. new daily cases**	**Date of peak**	**New daily cases at end of AL4**	**Cumulative reported cases**	**Total deaths**	***P(elim)*, 5 weeks after end of AL3**
Actual	**15-Mar**	**19-Mar**	**25-Mar**	**13-May**	**84**	**25-Mar**	**3**	**1502**	**21**	**-**
0	15-Mar	19-Mar	25-Mar	13-May	80 [67, 99]	31-Mar [26-Mar, 02-Apr]	4 [1, 8]	1448 [1208, 1796]	23 [14, 33]	0.66
1	15-Mar	19-Mar	20-Mar	8-May	69 [61, 79]	26-Mar [25-Mar, 26-Mar]	4 [1, 7]	953 [839, 1132]	14 [8, 21]	0.63
2a	15-Mar	19-Mar	30-Mar	18-May	108 [84, 139]	06-Apr [01-Apr, 09-Apr]	7 [3, 12]	2373 [1918, 2999]	39 [26, 55]	0.57
2b	15-Mar	19-Mar	4-Apr	23-May	179 [137, 233]	11-Apr [09-Apr, 14-Apr]	12 [6, 19]	3988 [3161, 5115]	67 [48, 91]	0.38
2c	15-Mar	19-Mar	14-Apr	28-May	503 [382, 661]	21-Apr [20-Apr, 23-Apr]	34 [22, 49]	11534 [8854, 15048]	200 [147, 266]	0.07
3	10-Mar	19-Mar	25-Mar	13-May	79 [67, 97]	31-Mar [26-Mar, 02-Apr]	4 [1, 8]	1422 [1194, 1765]	22 [14, 32]	0.66
4	15-Mar	24-Mar	25-Mar	13-May	91 [77, 110]	01-Apr [31-Mar, 02-Apr]	5 [1, 9]	1594 [1359, 1934]	25 [16, 35]	0.55
5a	10-Mar	19-Mar	20-Mar	8-May	68 [61, 79]	26-Mar [25-Mar, 26-Mar]	4 [1, 7]	941 [826, 1119]	14 [8, 21]	0.63
5b	15-Mar	24-Mar	30-Mar	18-May	120 [97, 152]	06-Apr [01-Apr, 08-Apr]	7 [3, 12]	2501 [2069, 3121]	41 [28, 56]	0.53
6	15-Mar	19-Mar	-	-	47592 [47240, 47962]	14-Jun [11-Jun, 17-Jun]	1127 [841, 1492][1]	60443 [45761, 79201][2]; 1,812,900 [1,809,600, 1,816,300][3]	1187 [891, 1565][2]; 31905 [31606, 32204][3]	0.00[4]

[1]*Evaluated on 27th April 2020 (end of actual AL4); continues to increase after this date.*
[2]*Evaluated on 13th May 2020 (end of actual AL3); continues to increase after this date.*
[3]*Evaluated at end of outbreak. Across all realisations, the outbreak had run its full course by approx. October 2020, on average, and the last case reported by 20 December 2020 at the latest.*
[4]*Evaluated on 18th June 2020 (5 weeks after end of actual AL3).*

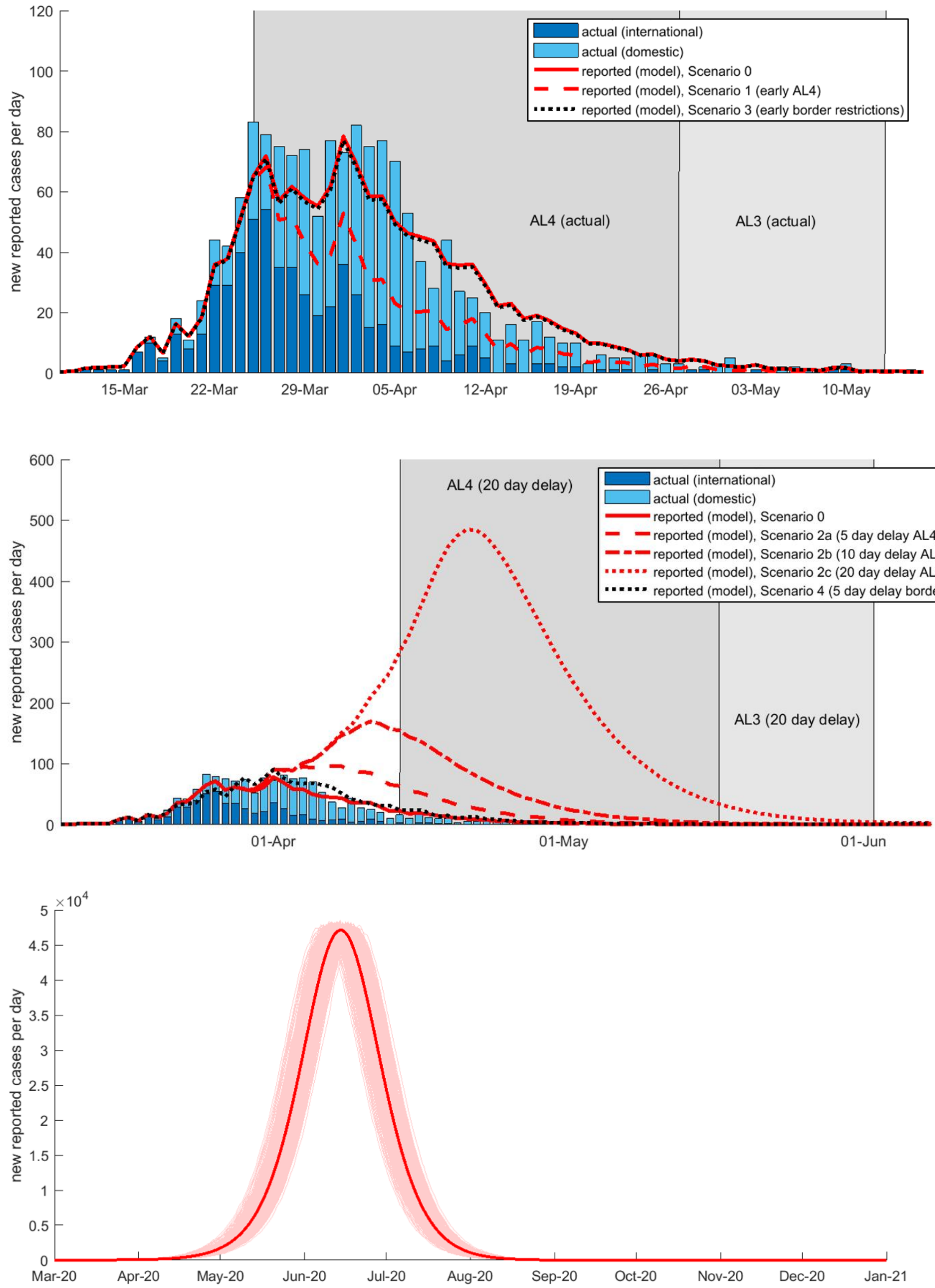

Figure 1: Effect of alternative timings of interventions on the trajectory of the outbreak. *Number of new reported cases per day predicted by the model alongside observed reported domestic (light blue bars) and international cases (dark blue bars) (data source: MoH). Model simulated for interventions implemented on their actual start dates and for alternative scenarios with different timings of AL4, border restrictions or border closure* ***Top:*** *Scenarios with AL4 started 5 days early (border restrictions and closure on actual start dates) (red dashed; Scenario 1) compared with a scenario where border restrictions were implemented five days early (border closure on actual start date) (red dotted; Scenario 3).* ***Middle:*** *Delayed start to Alert Level 4 (delays of 5, 10 and 20 days; Scenarios 2a-c; red broken lines) (with border restrictions and closure on actual start dates). Five day delay to*

border closure (with border restrictions and AL4 on actual start dates) (black dotted line; Scenario 4). ***Bottom:*** *No AL4/3 restrictions (border restrictions and closure on actual start dates; Scenario 6) results in an uncontrolled outbreak; faint red lines show the outbreak in individual realisations of the model, bold red line is the average over all 5000 simulations. Note, y-axis scale differs between figures.*

infectiousness during AL3. These subclinicals do not appear in the numbers of reported cases but will reduce the probability of elimination. If this international case outlier is excluded from the data, the model predicts a very similar probability of elimination in both scenarios.

Scenario 2: Delayed AL4

Delaying the move into Alert Level 4 would have led to a higher peak in daily new cases, and greater cumulative totals of cases and deaths. For a delay of 20 days (Scenario 2c), the outbreak would have reached a considerably higher maximum of close to 500 daily new cases (cf. 80 cases in Scenario 0; Table 3, Fig. 1 and Fig. 2). This number would certainly have overwhelmed the contact tracing system, which was already pushed close to capacity in places by the 70-80 daily new cases in late March (Verrall, 2020). After a week in AL4, case numbers would start to decline and by the end of the 4 weeks in AL4 daily new cases would still have been as high as 34 [22, 49] (close to the actual number of domestic daily reported cases when New Zealand went into AL4 on 25 March). By the end of the 7 week period of stringent restrictions (i.e. end of AL3) the incidence would have dropped to approximately 4 new cases per day (Fig. 1), but the cumulative total could have climbed to 11,534 [8854, 15048] reported cases and 200 [147, 266] deaths, substantially more than Scenario 0 and the 1,502 cases and 21 deaths actually reported on 13 May. Additionally, the probability of elimination 5 weeks after the end of AL3 was only 7%, much lower than Scenario 0.

Scenario 3: Early border restrictions

We next investigated a scenario where border restrictions were put in place 5 days earlier, but border closure and AL4 were started on their actual dates. Border restrictions would therefore have been in place for 9 days (cf. actual 4 days) before the border was closed. Our model predicted this would have had very little impact for the initial trajectory (Fig. 1) or eventual size of the outbreak, with values for all key measures very similar to those in Scenario 0 (Table 3). This finding suggests that key measures are more sensitive to varying the timing of AL4 than to the timing of border restrictions. In reality, out of the 563 international cases who arrived prior to the start of MIQ and could have contributed to local transmission, only 78 (14%) arrived before border restrictions were implemented on 15 March and were not required to self-isolate. Furthermore, out of these 78 cases, 52 arrived between 10 and 15 March and 19 of these were reported to have voluntarily self-isolated immediately on arrival (the model simulates these 19 cases as being self-isolated on arrival in all scenarios). Therefore, under this scenario, only an additional 33 international cases have their infectiousness reduced by early self-isolation requirements. This reduction is not sufficient to prevent an outbreak, nor does it reduce transmission to an extent where AL4/3 restrictions would not have been necessary to control the outbreak.

Scenario 4: Delayed border closure

Under a scenario where closure of the border (to all except returning residents and citizens) was delayed by 5 days (24 March; 9 days after border restrictions and 1 day before AL4), our model predicted slightly worse outcomes, on average, for key measures than were predicted in Scenario 0. However, due to the stochasticity of individual simulations, the range of key measures always had overlap with the Scenario 0 values and actual values, suggesting that a 5 day delay to border closure alone would not have made a significant difference. A delayed border closure did, however, have a greater impact for the probability of elimination 5 weeks after AL3 restrictions were relaxed, which was only 55%, compared to 66% chance in Scenario 0. This reduced probability of elimination is partly due to the additional international clinical cases (captured in the key measures of reported cases) and international subclinicals (not captured in reported cases) arriving prior to the delayed border closure. It is also likely affected by the international case outlier with the pre-MIQ arrival date and late onset date, discussed above.

Scenario 5: Change in timing of AL4, border restrictions and closure

After varying the timing of interventions individually, we considered the effects of varying timings for two interventions. If border restrictions were implemented 5 days early and AL4 came into effect 5 days early (Scenario 5a), this would have led to outcomes very similar to those predicted in Scenario 1 (where only AL4 started early) (Table 3). This again suggests that results are more sensitive to changes in timing for the start of AL4 than to an earlier start to border restrictions.

In contrast, if border closure and the start of AL4 had both been delayed by 5 days (Scenario 5b), outcomes would have been worse than a delay in only one of these interventions (cf. Scenarios 2a and 4). Daily new cases would have reached a larger maximum of 120 [97, 152] cases on 6 April and by the end of the 7 week period in AL4/3, there would have been close to 1,050 more cases in total and nearly 20 more deaths than in Scenario 0 (Table 3). The probability of elimination 5 weeks after AL3 would have also been reduced to 53%.

Scenario 6: No AL4

Finally, we explored the impact of only having border restrictions and border closure in place, but without implementing AL4/3. Under this scenario, the international cases who arrived prior to 9 April and were either in self-isolation or were not isolated have a chance of seeding an outbreak which, without AL4/3 measures to reduce R_{eff} below one, leads to community transmission and a large uncontrolled outbreak. New Zealand would have seen close to 1127 [841, 1492] new cases per day by 27 April, the date on which New Zealand moved from AL4 to AL3 in reality. By 13 May (the date on which New Zealand moved from AL3 to AL2), there could have been over 60,000 cumulative reported cases and over 1100 deaths. New cases would have continued to increase, reaching a peak of 47,592 [47,240, 47,962] daily new cases on 14 June (Table 3). By the end of the outbreak, around October 2020 on average, there could have been over 1.81 million reported cases in total and 31,905 [31,606, 32,204] deaths. No simulations resulted in elimination by 18 June (5 weeks after end of actual AL3), indicating a 0% chance of COVID-19 having been eliminated by this time, compared to the 66% chance on this date in Scenario 0.

Sensitivity analysis

We assessed the effect that different lengths of delay (in days) until the start of AL4 (Fig. 2) had on key measures: maximum load on contact tracing system; cumulative total reported cases; total infected cases (including both clinical and subclinical); total deaths at end of AL3; and probability of elimination 5 weeks after the end of AL3. Measures of numbers of cases and deaths increased exponentially with increasing delay to AL4, emphasising the importance of acting quickly to reduce the risk of large outbreaks arising. Probability of elimination decreased linearly with increasing delays to AL4. Counter-intuitively, earlier starts to AL4 slightly reduced the probability of elimination; again, this is caused by the international case outlier discussed previously. If the outlier is excluded from the international case data, the predicted probability of elimination is insensitive to AL4 starting 1 to 5 days early.

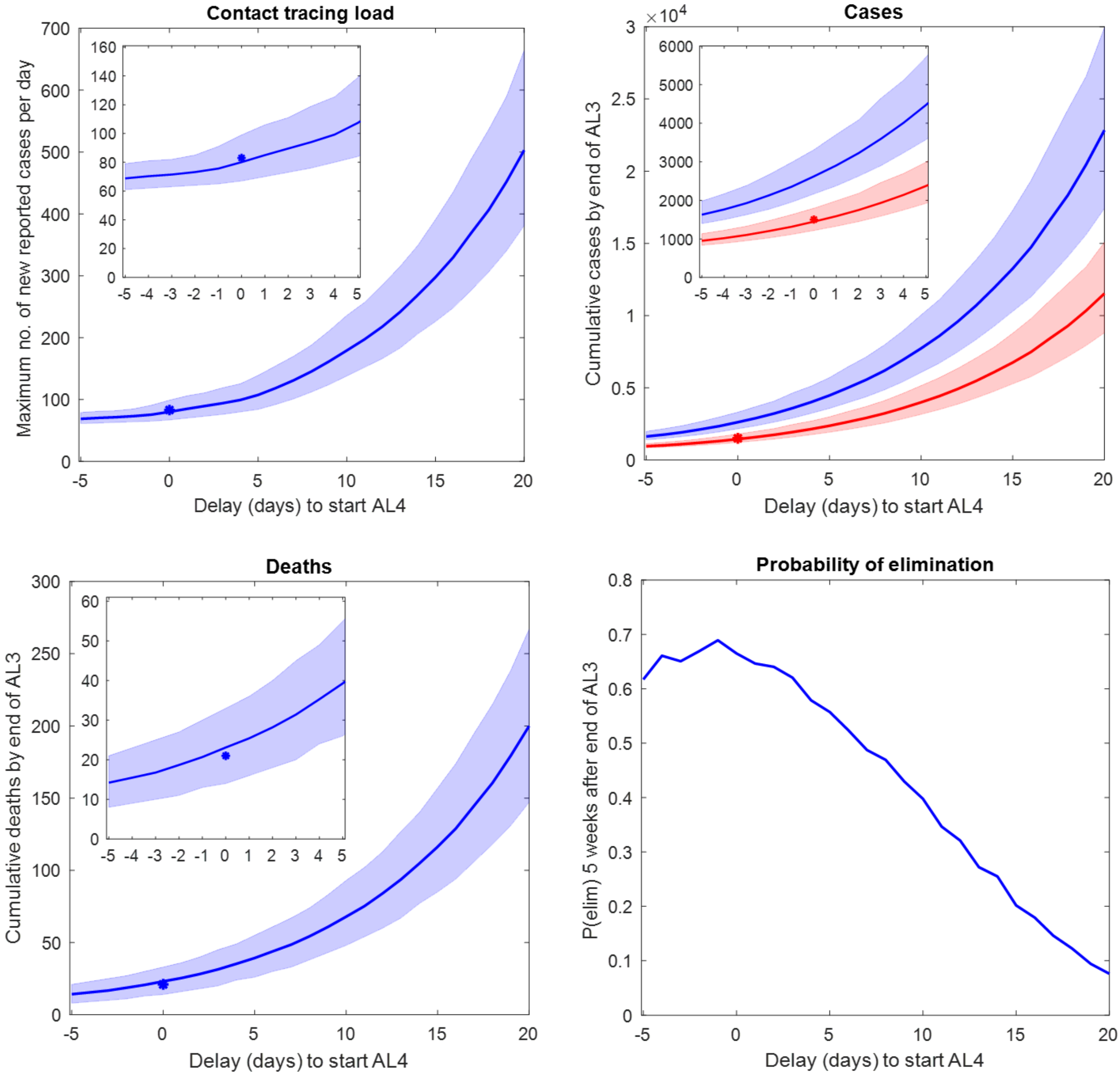

Figure 2: Sensitivity of predicted cases and deaths to varying the delay until start of Alert Level 4, up to a maximum delay of 20 days. *A negative delay of -5 days represents starting Alert Level 4 5 days early (20th March 2020). Border restrictions and closure were implemented on the same dates as actually occurred.* ***Top, left:*** *Maximum load on contact tracing system (measured as maximum number of new reported cases per day) predicted by the model (blue line) and actual maximum number of daily reported cases (asterisk).* ***Top, right,:*** *Cumulative number of infected individuals (both clinical and sub-clinical) (blue line) and reported cases (red line) predicted by the model and actual number of reported cases (red asterisk).* ***Bottom, left****: Cumulative number of deaths predicted by the model (blue line) and actual number (blue asterisk).* ***Bottom, right:*** *Probability of elimination, P(elim), 5 weeks after the end of AL3. Shaded regions indicate the interval range in which 90% of simulation results are contained. Note, y-axis scale differs between figures. Insets show close-ups of results for delays from -5 to 5 days.*

Introducing border restrictions ten days earlier still results in an outbreak and gives very similar results to Scenario 3 (5 days early), with a maximum of 77 [65, 94] new daily cases, 1385 [1166, 1706] cumulative reported cases at the end of AL3, *P(elim)* = 0.68, and other measures the same as in Scenario 3. With border restrictions ten days earlier, the only difference compared to Scenario 3 is that an additional 16 cases who arrived between 5 and 10 March have their infectiousness reduced (a further 2 cases arriving in this 5-day period were voluntarily self-isolated on arrival in reality, so are simulated with self-isolation on arrival in all scenarios). This restriction has little impact on the overall contribution to local transmission by all 563 international cases who arrive prior to the start of MIQ.

We also tested the sensitivity of all key measures to using different values of R_{eff} under AL3 (Table S2; R_{eff} = 1.1, 0.95 and 0.7). Different choices of AL3 R_{eff} had very little effect on predicted cumulative totals of cases at the end of AL3 and no effect on total deaths at end of AL3. However, the predicted probability of elimination was sensitive to varying AL3 R_{eff}; for all scenarios, assuming a lower R_{eff} = 0.7 (more effective AL3) gave a *P(elim)* that was approximately 0.14 higher than with R_{eff} = 0.95, while a higher R_{eff} = 1.1 (less effective AL3) reduced *P(elim)* by approximately 0.07.

Discussion

New Zealand's decision to act quickly and to implement stringent restrictions to reduce SARS-CoV-2 transmission meant that, to date, New Zealand has experienced amongst the lowest mortality rates reported worldwide (Kontis et al., 2020). On 8 June 2020, nearly 11 weeks after AL4 was initiated, New Zealand declared elimination of COVID-19. Over the course of the March-April outbreak, a total of 1504 cases and 22 deaths were reported before elimination was achieved. Our results suggest that the timing of Alert Level 4 is a much stronger driver of reductions in daily new cases than timings of border restrictions and closure. This finding makes sense because the effect of AL4 in the model is to greatly reduce R_{eff} for all cases, domestic and international arrivals, to 0.35, while border restrictions reduce the delay until case isolation of international cases only (i.e. international cases have their infectiousness reduced earlier) and border closure reduces the daily numbers of international cases only. Out of the scenarios we considered, an earlier start to AL4 by 5 days resulted in the greatest reduction in numbers of cases and deaths, with approximately 500 fewer cases in total and 10 fewer deaths. However, in reality, the rapid escalation of the COVID-19 situation in mid-March may have made an earlier start to AL4 impractical and would have allowed less time to prepare for ongoing provision of essential services under AL4.

Introducing border restrictions requiring 14-day self-isolation for international arrivals earlier than 15 March would have been unlikely to have much impact on the trajectory of New Zealand's March-April outbreak, unless such measures were started prior to the first case on 26 February and used methods that were particularly effective (notably full MIQ). The 563 international cases arriving between 15 March and 9 April were already required to self-isolate; had border restrictions been in place prior to the arrival of New Zealand's first case, this would have required self-isolation for, at most, an additional 56 international cases (22 cases who arrived prior to 15 March self-isolated voluntarily immediately on their arrival). In mid-March, there was a lower global prevalence of COVID-19 and between 2 and 12 cases arrived at the border each day in the week prior to 15 March. With a higher global prevalence and correspondingly higher numbers of international cases arriving per day, earlier implementation of border restrictions may have had a greater impact than our model predicted for this outbreak. Self-isolation is less stringent than MIQ and relies heavily on public compliance. Without additional safety nets, such as official monitoring and support for people who are self-isolating, there is a greater risk of the virus spreading into the community than in MIQ facilities. For example, risk of non-compliance may be higher for individuals who are concerned about loss of income (Bodas & Peleg, 2020). Without Alert Level restrictions in place to require strong community-wide social distancing, any infected individuals who do not self-isolate effectively are more likely to spark an outbreak. Self-isolation restrictions for international arrivals can therefore reduce the frequency of cases leaking into the community (James et al, 2020c) but are unlikely to be sufficient to prevent an outbreak entirely, unless additional measures are also put in place.

Delaying border closure by 5 days could have led to a slightly larger outbreak, but not as large as if AL4 had been delayed by 5 days. The full effect on local transmission potential of the additional international cases expected under a delayed border closure was partially dampened because international cases arriving after 9 April were still placed in MIQ and assumed not to contribute to community transmission. If the timing of this MIQ policy was also delayed, a larger outbreak may have occurred, but we did not model such a scenario here. If the start of AL4 had been delayed by 20 days, our results suggest New Zealand could have experienced over 11,500 reported cases and 200 deaths, reducing the chance of elimination to only 7%. As with other severe viral disease, the infection fatality risk for COVID-19 is greater for Māori and Pacific peoples (close to 50% higher for Māori than for non-Māori) (Steyn et al., 2020; Wilson et al., 2012; Verrall et al., 2010). Therefore, in scenarios resulting in significantly higher numbers of COVID-19-related deaths (e.g. Scenario 2c), Māori and Pacific communities would likely have been disproportionately affected, however a population-structured model would be required to assess this consequence in detail. Delaying AL4 would have also increased the chance of a longer lockdown period being required to reduce daily new case numbers to low levels. With a 20 day delay to AL4, New Zealand could still have been experiencing close to 35 new reported cases per day at the end of AL4. While in reality, a 33-day period in AL4 was sufficient to reduce daily new cases to below 10, and the Government announced an easing to AL3, these higher case numbers predicted for a delayed start to AL4 may have motivated an extension to the lockdown to allow more time for cases to drop below a safe threshold.

In terms of the key measures we considered, the counterfactual scenario with no AL4/3 restrictions (Scenario 6) had disastrous outcomes, including close to 2 million reported cases and tens of thousands of deaths. This demonstrates that: 1) under the conditions (e.g. level of pandemic preparedness and global COVID-19 prevalence) particular to New Zealand's March – April outbreak, border restrictions and border closure alone would not have been sufficient to control the outbreak; and 2) New Zealand's national lockdown restrictions in combination with its border management, rapid testing and contact tracing, were effective measures that prevented a considerably larger and more prolonged outbreak (i.e. Scenario 6) from occurring during that period.

Our model uses a value of $R_{eff}=0.35$ during AL4, which was estimated by Binny et al (2020b) by fitting the model to data, and is consistent with a later estimate of R_{eff} from reconstructions of the epidemiological tree (James et al., 2020c). This is a relatively low value of R_{eff} compared to other countries who implemented interventions roughly equivalent to AL4 (Flaxman et al, 2020; Binny et al, 2020a). A combination of a highly effective social distancing in AL4, fast contact tracing, effective case isolation, and the fact that the outbreak occurred at the end of the Southern hemisphere summer, likely contributed to this low R_{eff} (James et al, 2020b). For scenarios where the load on contact tracing exceeded system capacity (e.g. Scenario 2c with a maximum 500 daily new cases), this effect would have likely resulted in longer delays to isolation of cases and a higher R_{eff}. We did not attempt to model this potential feedback effect and so our results for scenarios where contact tracing system capacity is exceeded may underestimate the size of the outbreak. Our model assumed a relatively high and constant proportion (75%) of clinical cases are detected and reported. In reality, this proportion can vary over time as testing and contact tracing policies are revised, or as contact tracing and health systems become overloaded in a large uncontrolled outbreak (e.g. Scenario 6). This makes it difficult to benchmark predicted case numbers against empirical data from outbreaks in other countries, where testing and contact tracing regimes may differ from New Zealand. Infection fatality rates can also vary between different countries and over time, for example fatality rates can decrease as new knowledge, treatments and technologies become available. For simplicity, our model assumed a constant IFR of 0.88%, which is within the range of IFR estimates reported for other countries and very close to the median IFR reported for countries with COVID-19 mortality rates that are less than the global average (Ioannidis, 2020). We did not attempt to directly model the burden of COVID-19 on the healthcare system (e.g. numbers of cases requiring hospitalisation or intensive care), or the effects of an overwhelmed healthcare system. Once numbers of daily new cases requiring hospitalisation or ICU admission exceed New Zealand's healthcare system capacity, this could result in increased fatality rates and considerably more deaths (Plank et al, 2020a). These effects would have been most pronounced under the scenario with no AL4/3 restrictions.

It is important to note that, while we report average values for outbreak dynamics, each individual realisation of the stochastic model can deviate (sometimes widely) from the average behaviour. When case numbers are small, as they were in New Zealand, the predicted dynamics are particularly sensitive to fine-scale variations. While $R_{eff} < 1$ means that an outbreak will eventually die out, on average, it is still possible for a small number of cases to spark an outbreak in a particular stochastic realisation if interventions are relaxed too soon. Conversely, when case numbers are small, an outbreak can still die out by chance even when $R_{eff} > 1$. It is therefore important to account for this stochasticity when weighing the effectiveness and risks of different intervention strategies, for example by considering the probability of elimination. On 18 June, five weeks after AL3 restrictions were relaxed, the probability that community transmission of COVID-19 had been eliminated in model simulations was estimated to be 66% in Scenario 0. This estimate is calculated by finding the proportion of stochastic realisations that resulted in elimination. In reality, as the outbreak died out and more days with zero new cases were observed, this provided additional information about which trajectory New Zealand was most likely experiencing. Each additional consecutive day with no new reported cases reduced the likelihood of being on an upward trajectory. Making use of this information meant that the actual probability of elimination on 18 June was estimated to be 95% higher than in Scenario 0 (Binny et al., 2020c). However, this estimate required up-to-date information about recent case numbers. The results reported in this paper compare average outcomes under different scenarios, which is appropriate for evaluating the effect of alternative actions and guiding future decision making. In general, for the other scenarios we explored, bringing in earlier interventions had very little impact on probability of elimination, while delaying border closure or AL4 reduced the chance of elimination.

Our results are important for reflecting on the effectiveness of intervention timing in New Zealand's COVID-19 response, relative to alternative scenarios, to help guide future response strategies. Early intervention was critical to the successful control of New Zealand's March-April outbreak. For modelling future disease outbreaks, epidemiological parameters should be updated to reflect changes in national pandemic preparedness (e.g. improved policy and response plans) and behavioural changes influencing the dynamics of future outbreaks. For instance, the degree of compliance with alert level restrictions in future may differ dramatically from the March-April outbreak, resulting in different values of R_{eff}. Further work is needed to explore the social dynamics affecting transmission and the effectiveness of interventions, for instance whether wearing masks in public spaces becomes more common, or whether more people will choose to work from home or avoid travel if a suspected new outbreak is reported or if government action is perceived to be inadequate.

The key measures of outbreak dynamics assessed here should be considered alongside other measures of economic, social and health impacts (e.g. job losses, consumer spending, impacts for mental health, rates of domestic violence or disrupted education). Particular attention needs to be given to identifying vulnerable groups who may experience inequitable impacts so that future policies can be tailored to support these groups. At the end of AL3, health benefits (e.g. number of cases and deaths avoided) differed between scenarios. For cost-benefit analyses, age-dependent morbidity and mortality rates of COVID-19 (Kang & Jung, 2020) allow numbers of cases and deaths to be quantified in terms of disability-adjusted life years (DALYs) avoided (or quality-adjusted life years gained), which can (with obvious issues) be converted to monetary units to facilitate comparison with economic costs. Because the duration spent under AL4/AL3 was fixed at 7 weeks for Scenarios 0-5, the short-term economic costs of the different scenarios would have been similar, so we did not convert health benefits into DALYs here. After the end of AL3, benefits and costs would differ between scenarios depending on the value of R_{eff} for AL1-2 and on whether or not elimination was achieved. Increased levels of activity and contact rates under AL1-2 mean that R_{eff} is very likely to have been greater than one. In scenarios with lower probabilities of elimination, it is more likely that New Zealand would continue to experience new cases while under AL1-2 which, with $R_{eff} > 1$, would likely lead to another outbreak and require a second lockdown (with its associated costs). Conversely, scenarios with higher probabilities of elimination mean there is a greater chance of the outbreak dying out entirely and less risk of a second lockdown being required. Future work could consider the costs and benefits of alternative scenarios where the duration of time spent in AL4 and AL3 is dictated by the need to achieve a certain threshold probability of elimination.

Acknowledgements

The authors acknowledge the support of StatsNZ, ESR, and the Ministry of Health in supplying data in support of this work. We are grateful to Samik Datta, Nigel French, Markus Luczak-Roesch, Melissa McLeod, Anja Mizdrak, Fraser Morgan and Matt Parry for comments on an earlier version of this manuscript. This work was funded by the Ministry of Business, Innovation and Employment and Te Pūnaha Matatini, New Zealand's Centre of Research Excellence in complex systems.

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Appendix

Table S1: Parameters used for model simulations and their sources.

Parameter	**Value**	**Source**
Distribution of generation times	$Weibull(\text{scale} = 5.67, \text{shape} = 2.83)$	Feretti et al (2020)
Distribution of exposure to onset (days)	$T_1 \sim \Gamma(\text{shape} = 5.8, \text{scale} = 0.95)$	Lauer et al (2020)
Distribution of onset to isolation (days) (from data)	$T_2 \sim Exp(\text{mean} = 2.18)$	Davies et al (2020a)
Distribution from isolation to reporting	$\Gamma(\text{shape} = 1, \text{scale} = 6)$	Fitted to data
Reproduction number for clinical infections (no case isolation or control)	$R_{clin} = 3$	Davies et al (2020a)
Reproduction number for subclinical infections	$R_{sub} = 1.5$	Davies et al (2020a)
Relative infectiousness of subclinical cases	$R_{sub}/R_{clin} = 50\%$	Davies et al (2020a)
Proportion of subclinical infections	$p_{sub} = 33\%$	Davies et al (2020b); Byambasuren et al (2020); Lavezzo et al (2020)
Relative infectiousness after self-isolation (home quarantine); and after MIQ	$c_{iso} = 65\%$; $c_{MIQ} = 0\%$	Davies et al (2020a)
Proportion of clinical cases detected and reported	$p_R = 75\%$	Price *et al.* (2020); and estimated from limited NZ data
Individual heterogeneity in transmission rate	$Y_K = 0.5$ (i.e. moderate super-spreading)	Endo et al (2020); Lloyd-Smith et al (2005)
Infection fatality rate (IFR)	0.88%	Age-specific IFR estimates from Verity et al (2020), fitted to NZ's age distribution from 2018 Census data
Transmission rate relative to no population-wide control, at AL 1, 2, 3 and 4; and in the period prior to AL4	*C(t)* = 1, 0.7, 0.4 and 0.147 (corresponding to R_{eff} = 2.37, 1.66, 0.95 and 0.35); and *C(t)* = 0.75 (R_{eff} =1.8)	Flaxman *et al*, 2020; Binny et al, 2020a; Binny et al, 2020b; and limited NZ data

Table S2: Key measures from scenarios of early or delayed implementation of policy interventions: the maximum number of daily new cases, date on which the peak occurs, the number of daily new cases at the end of the Alert Level 4 period, the cumulative number of cases and the total number of deaths at the end of the simulated 7 week period of Alert Level 4/3 restrictions. For each measure, except P(elim), the mean value from 5000 simulations is reported alongside the interval range, in parentheses, in which 90% of simulations results are contained.

Scenario	**R_{eff} in AL3**	**Max. new daily cases**	**Date of peak**	**New daily cases at end of AL4**	**Cumulative cases**	**Total deaths**	***P(elim)*, 5 weeks after end of AL3**
Actual	**Unknown**	**84**	**25-Mar**	**3**	**1502**	**21**	**-**
0	0.70	80 [67, 98]	31-Mar [26-Mar, 02-Apr]	4 [1, 8]	1442 [1210, 1785]	23 [14, 33]	0.79
	0.95	80 [67, 99]	31-Mar [26-Mar, 02-Apr]	4 [1, 8]	1448 [1208, 1796]	23 [14, 33]	0.66
	1.10	80 [67, 99]	31-Mar [26-Mar, 02-Apr]	4 [1, 8]	1445 [1212, 1795]	23 [14, 33]	0.60
1	0.70	69 [61, 79]	26-Mar [25-Mar, 26-Mar]	4 [1, 7]	954 [837, 1140]	14 [8, 21]	0.74
	0.95	69 [61, 79]	26-Mar [25-Mar, 26-Mar]	4 [1, 7]	953 [839, 1132]	14 [8, 21]	0.63
	1.10	69 [62, 80]	27-Mar [25-Mar, 26-Mar]	4 [1, 7]	954 [838, 1135]	14 [8, 21]	0.55
2a	0.7	107 [85, 138]	06-Apr [01-Apr, 09-Apr]	7 [2, 12]	2374 [1939, 2987]	39 [26, 55]	0.71
	0.95	108 [84, 139]	06-Apr [01-Apr, 09-Apr]	7 [3, 12]	2373 [1918, 2999]	39 [26, 55]	0.57
	1.10	108 [84, 139]	06-Apr [01-Apr, 09-Apr]	7 [3, 12]	2376 [1928, 3006]	39 [26, 54]	0.48
2b	0.70	179 [137, 235]	11-Apr [09-Apr, 14-Apr]	12 [6, 19]	3998 [3150, 5162]	68 [48, 92]	0.55
	0.95	179 [137, 233]	11-Apr [09-Apr, 14-Apr]	12 [6, 19]	3988 [3161, 5115]	67 [48, 91]	0.38
	1.10	179 [137, 235]	11-Apr [09-Apr, 14-Apr]	12 [6, 19]	3992 [3146, 5176]	67 [48, 92]	0.33
2c	0.70	503 [378, 663]	21-Apr [20-Apr, 23-Apr]	34 [22, 49]	11514 [8847, 15038]	200 [148, 268]	0.21

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	0.95	503 [382, 661]	21-Apr [20-Apr, 23-Apr]	34 [22, 49]	11534 [8854, 15048]	200 [147, 266]	0.07
	1.10	503 [377, 659]	21-Apr [20-Apr, 23-Apr]	34 [21, 49]	11525 [8846, 14986]	200 [147, 264]	0.045
3	0.70	79 [66, 97]	31-Mar [26-Mar, 02-Apr]	4 [1, 8]	1417 [1194, 1755]	22 [14, 32]	0.79
	0.95	79 [67, 97]	31-Mar [26-Mar, 02-Apr]	4 [1, 8]	1422 [1194, 1765]	22 [14, 32]	0.66
	1.10	79 [66, 97]	31-Mar [26-Mar, 02-Apr]	4 [1, 8]	1414 [1189, 1735]	22 [14, 32]	0.62
4	0.70	91 [77, 110]	01-Apr [01-Apr, 02-Apr]	5 [1, 8]	1589 [1353, 1946]	25 [16, 35]	0.69
	0.95	91 [77, 110]	01-Apr [31-Mar, 02-Apr]	5 [1, 9]	1594 [1359, 1934]	25 [16, 35]	0.55
	1.10	88 [74, 107]	01-Apr [29-Mar, 02-Apr]	5 [1, 9]	1597 [1363, 1945]	25 [16, 35]	0.47
5a	0.70	68 [61, 79]	26-Mar [25-Mar, 26-Mar]	4 [1, 7]	940 [828, 1115]	14 [8, 21]	0.76
	0.95	68 [61, 79]	26-Mar [25-Mar, 26-Mar]	4 [1, 7]	941 [826, 1119]	14 [8, 21]	0.63
	1.10	68 [61, 79]	26-Mar [25-Mar, 26-Mar]	4 [1, 7]	941 [825, 1118]	14 [8, 21]	0.55
5b	0.70	123 [99, 155]	05-Apr [01-Apr-, 08-Apr]	7 [3, 13]	2545 [2096, 3170]	41 [28, 57]	0.68
	0.95	120 [97, 152]	06-Apr [01-Apr, 08-Apr]	7 [3, 12]	2501 [2069, 3121]	41 [28, 56]	0.53
	1.10	124 [100, 157]	06-Apr [02-Apr, 08-Apr]	7 [3, 13]	2585 [2124, 3217]	42 [29, 58]	0.41

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Table S3: Summary of restrictions under New Zealand's COVID-19 four-tier Alert Level system and an elimination strategy. Published on the Covid19.govt.nz website. Essential services (including supermarkets, health services, emergency services, utilities and goods transport) continue to operate at all Levels.

Alert Level	Measures
Level 4 - Lockdown	• Stay at home except for essential personal movement • Safe recreational activity allowed in local area. • Travel is severely limited. • All gatherings cancelled and public venues closed. • Businesses closed, except essential services and lifeline utilities. • Educational facilities closed. • Rationing of supplies and requisitioning of facilities possible. • Reprioritisation of healthcare services.
Level 3 - Restrict	• Stay at home except for essential personal movement - including going to work, school or for local recreation. • Work from home if possible. • Low risk local recreation activities allowed. • Inter-regional travel highly limited (e.g. allowed for essential workers, with limited exemptions for others). • Public venues closed (e.g. libraries, museums, cinemas, food courts, gyms, pools, playgrounds, markets). • Gatherings of up to 10 people allowed but only for wedding services, funerals and tangihanga, with physical distancing and public health measures maintained. • Two-metre physical distancing outside home. One metre in controlled environments, e.g. schools and workplaces. • People must stay within their immediate household bubble, but can expand this to reconnet with close family/whānau, or bring in caregivers, or support isolated people. This extended bubble should remain exclusive. • Businesses can open premises, but cannot physically interact with customers. • Schools (years 1 to 10) and Early Childhood Education centres can safely open but with limited capacity. Children should learn from home if possible. • Healthcare services use virtual, non-contact consultations where possible. • People at high risk of severe illness (older people or those with pre-existing medical conditions) are encouraged to stay at home and take extra precautions when leaving home. They may choose to work.

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