The estimated likelihood of eliminating the SARS-CoV-2 pandemic in Australia and New Zealand under current public health policy settings: an agent-based-SEIR modelling approach.

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Research in Context

Evidence before the study: An extensive review of data on SARS-COV-2 viral transmission was attained from the Governments of Australia and New Zealand along with published reports from China, Italy and the United Kingdom. Almost all published reports adopted SEIR transmission models. Although these models are reasonably robust, they are limited by their inability to assess dynamic interactions between members of the population during the pandemic; a necessary attribute when exploring the utility of implemented public health responses.

Added value of the study: We applied an agent-based SEIR model to resolve previously unanswered questions namely, what is the prospect of eliminating SARS-COV-2 under currently implemented public health responses and when can restrictions imposed by the current strategies be halted or partially removed? This paper provides important insights that will assist policymakers with decisions in relation to relaxing currently implemented physical distancing measures and the likely consequences in relation to the potential elimination of SARS-COV-2. The authors offer the model for use and adaptation by other countries wanting to understand the likely disease progression and policy impact.

Implications of all the available evidence: The findings highlight that in Australia and New Zealand, Government imposed public health responses provide the potential to eliminate the SARS-COV-2 infection if adherence to the response is maintained. However, a high probability of elimination is contingent on maintaining current strict physical distancing restrictions for approximately 100 days, before relaxing physical distancing and relying on border control, surveillance and contact tracing. These findings highlight the need for additional measures that could plausibly reduce the physical distancing period to less than 100 days, notably the implementation (as is happening) of much improved testing and contact tracing. This is timely evidence that can influence the trajectory of the pandemic in these countries.

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Abstract

Background: For countries with strong border control and an epidemic that is not yet advanced, there is an opportunity to eliminate SARS-CoV-2 that is causing the COVID-19 pandemic. We estimate the probability of elimination of SARS-COV-2 under i) strict distancing policies implemented in New Zealand and Australia on the 26th and 28th March, respectively, continuing indefinitely; and ii) the same policy, but with physical distancing decaying over 60 days post-26th and 28th March.

Methods: We developed an agent-based SEIR model calibrated to current government-reported models of SARS-CoV-2 disease progression in Australia and New Zealand. The model simulated key aspects of both country's populations, disease, and social dynamics, as well as the mechanism and effect of public health policy responses on the mitigation of SARS-CoV-2.

Findings: Under maintained strong physical distancing, elimination is achieved with 90% probability by July 10th in Australia (104 days post restrictions, 95% SI: 83% - 96%) and July 14th in New Zealand (110 days post restrictions, 95% SI: 87% - 99%). An 80% probability of elimination is achievable in Australia on July 3rd (97 days post restrictions, 95% SI: 73% - 91%) and on the 2nd of July (98 days post restrictions, 95% SI: 70% - 88%) in New Zealand.

However, under our scenario of decaying adherence to physical distancing from implementation to 60 days post restrictions, a rebound in SARS-CoV-2 infections (i.e., a second wave) is likely in both countries. At 100 days, the probability of elimination is 18% in Australia and 16% in New Zealand.

Interpretation: The findings highlight that it is possible to eliminate SARS-CoV-2 transmission within these two countries. However, a high probability of elimination is contingent on maintaining current strict physical distancing restrictions for at least two months, before relaxing these restrictions and relying on border control, surveillance and contact tracing. It is plausible that this period could be reduced with the implementation (as is happening in both NZ and Australia) of much improved testing and contact tracing (e.g. with digital technologies).

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Introduction

The first notification of SARS-CoV-2 infections in Australia and New Zealand (NZ)[1] were January 26th and February 26th, 2020, respectively[2,3]. The public health response to managing the pandemic in both countries involves the testing of individuals showing symptoms of SARS-CoV-2 infection, isolating individuals with a positive polymerise chain reaction (PCR) test, and tracing and quarantining contacts. On a country-scale, comprehensive physical distancing strategies have been in place since March 28th in Australia[3] with people remaining at home other than for essential items and maintaining 1.5 metres between people when in public. In NZ, similar mass home quarantine was initiated on March 26th [4] which placed even tighter restrictions on individual movements than in Australia. Both countries have ongoing enhancements of the health system capacity, and extensive travel restrictions including the closure of country borders to non-residents and 14-day quarantine for the small number of international arrivals still permitted.

The public health response implemented in Australia and NZ initially focussed on mitigation (flattening the epidemic curve) by instituting the above strategies. But since then, the NZ strategy has explicitly become that of elimination[5]. In Australia, the recently announced strategy is that of "suppression/elimination"[6], and the recent declines in reported cases suggest that the "elimination strategy" could become the dominant approach.

The modelling implemented by both governments using transmission models which incorporate the susceptible-exposed-infected-recovered (SEIR) concept[7,8] have been invaluable in describing and comparing the health impact of pandemic scenarios. However, important questions remain unanswered that benefit from micro-simulation of individuals namely, the prospect of elimination of SARS-CoV-2 under the current strategies, and when restrictions can be halted or partially removed?

A limitation of the population-level macro-simulation models that informed government decision-making is their inability to manipulate or assess the effect of interactions between members of the population during the pandemic at an individual level, or the effect of targeted policies[9]. For example, macro-simulation models cannot easily capture the heterogeneity of individuals – such as the contact patterns of essential workers versus those largely isolated at home; an important phenomenon that will determine the feasibility of elimination. By modelling not just the disease, but behaviours that lead to disease transmission, we can better understand policy options for suppression/mitigation and elimination, and understand the likely patterns of disease progression among individuals with SARS-CoV-2[9] and the community at large. In this paper, we apply an agent-based model to estimate the probability of elimination of SARS-COV-2 under: i) strict distancing policies implemented in NZ and Australia on 26th and 28thth March, respectively, continuing indefinitely; and ii) the same policy, but with physical distancing decaying decaying over 60 days post 26th and 28th March (but ongoing border closure, testing and contact-tracing).

Methods

We applied disease transmission principles from models developed for the Australian[8] and NZ[7] Governments and integrated them into an agent-based SEIR model (ABM-SEIR) similar to models described elsewhere[10]. The ABM-SEIR model was scaled to the entire Australian (25 million) and NZ (5 million) populations and it modelled the requisite parameters to investigate the likelihood of SARS-CoV-2 progression and the likelihood of elimination in both countries. We consider elimination when the transmission is reduced to zero incidence of COVID-19 infections in Australia and NZ, with minimal risk of reintroduction[1].

The ABM-SEIR model has been built using the parameters from the pandemic in both countries and is capable of taking account of important factors that influence the SARS-CoV-2 infection such as physical distancing measures underpinning key government strategies now in place, as well as the transmission of the infection, and the time it takes to recover. The model has been built to simulate the dynamics of SARS-CoV-2 at either a country, state or local level. For the purpose of this paper, we have modelled the dynamics of SARS-CoV-2 at the country-level.

Model description

For each country, individual agents making up a synthetic population representing residents of either Australia or NZ were modelled. Each agent possessed demographic, behavioural, and social policy response characteristics uniquely assigned to them. Agents moved and interacted in the model based on stochastic processes or in response to policies reflecting government-imposed restrictions. Their aggregate behaviour, experiences (e.g., of infection and recovery) and actions were used to assess the effect of SARS-CoV-2 disease progression and suppression strategies across the populations.

Specifically, we estimated the dates by which each country is likely to achieve SARS-CoV-2 elimination under current policy settings with 60% confidence that the disease will be eliminated through to 90% confidence.

The computing demands and development time required to build and run a 1:1 scaled ABM-SEIR models representing millions of people is considerable, making analysis associated with rapid changes in policies and time-critical decision-making difficult in an unfolding pandemic. Hence, published models used to inform policy in the early stages of the pandemic in both the United Kingdom and Australia were adapted from existing influenza models[2,11]. Despite their influence and utility, they have also been criticized from the perspective of transparency (e.g., the model code is not available), scale (e.g., local vs national dynamics), and a limited incorporation of social and behavioural dynamics related to adherence that either facilitate or suppress SARS-CoV-2 spread[12]. Their ability to be applied outside their specific countries of origin is also limited.

In response, we developed and applied a flexible, multi-scale solution that begins at a local-scale (n=2500 people), and then scales up to a maximum representation of 25 million individuals (the Australian population) or 5 million (NZ's population). Because it is underpinned by stochastic processes, the ABM-SEIR model was run 1000 times to attain the reported results. We explored two scenarios for each country, namely: i) strict distancing policies implemented in NZ and Australia on 26th and 28th March, respectively, continuing indefinitely; and ii) the same policy, but with physical distancing decaying over 60 days post post-26th and 28th March (see Figure 1). All model iterations ran for 365 simulated days. Estimated average time to elimination with 95% simulation intervals (SI) is reported for Australia and NZ, alongside estimated dates for elimination with 80 and 90% likelihood. All programming, documentation, data and details related to the calculations, estimations and assumptions are available for download from the online repository (https://bit.ly/2XI3v3z).

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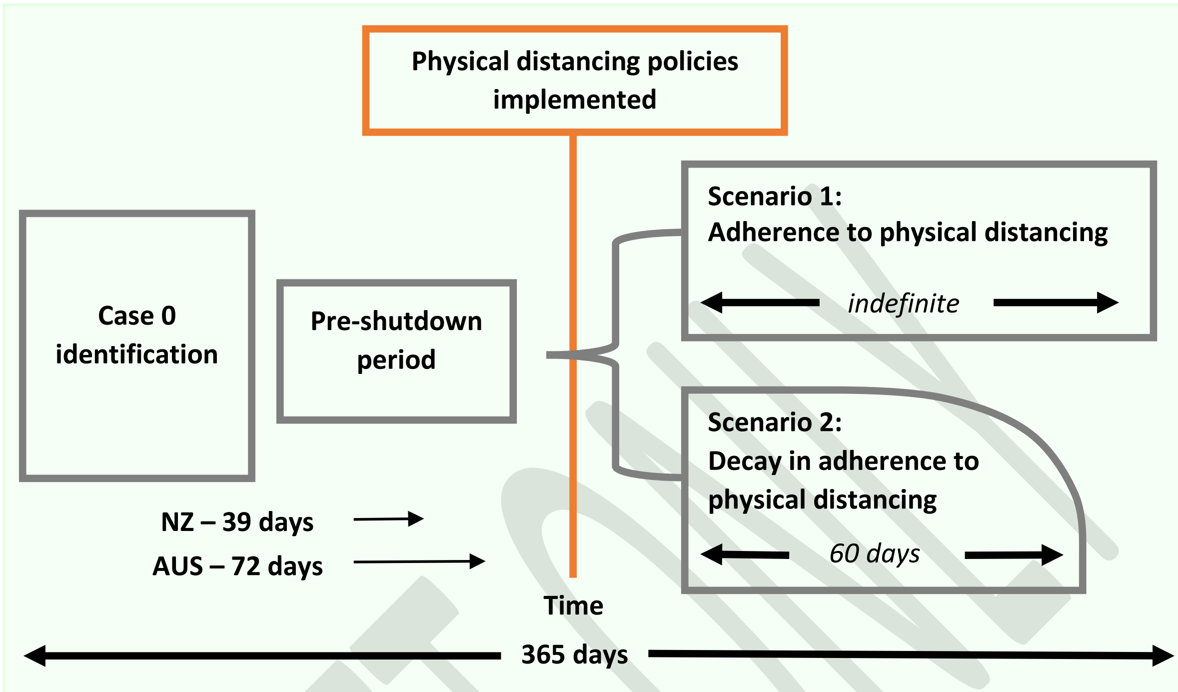

Figure 1. Representation of the 2 scenarios modeled for Australia and NZ.

The model was initially populated by 2500 people with 2495 people susceptible. Five people were classified as infected with the SARS-CoV-2 and could potentially infect others. In the early stage of the ABM-SEIR model, people moved at random headings throughout the local environment. If an infected person encountered a susceptible person, there was a probability of disease transmission from the infected to the susceptible person. This probability was tuned to produce early-stage (e.g., day 10 to 30) country-level doubling patterns approximating those reported for SARS-CoV-2 in the literature and approximating a basic reproduction number (R_0) value of between 2.2 to 2.7 [13,14], while also adjusting for overseas arrivals, which accounted for 50% of new cases. Imported cases began their illness duration in the model in a marginally advanced state compared with those who acquired their infection in the community. The mean duration of illness already elapsed for overseas cases at the time of their appearance in the model was drawn from a distribution of the incubation period of existing people. Based on estimates of asymptomatic case proportions, 50% of cases were classified as asymptomatic and demonstrated a transmission likelihood that was one third that of symptomatic cases (the remaining 50%).

Infected people experienced a uniquely assigned incubation period drawn from a log-normal distribution with a mean of 5 days and standard deviation (sd) of 0.44 days. Infected people were also assigned a period of illness duration that followed a log-normal distribution with a mean of 15 days and sd of 0.99 days. If infected, each person had a likelihood of complying with isolation requests drawn from a log-normal distribution with a mean of 95% and sd of 1%. Infected individuals also had a likelihood of death based on their age-group[15]. Deceased people were effectively 'hidden' from interacting with the remaining susceptible, infected and recovered population. Effective reproduction number (R*t*) values were calculated and reported on an individual basis for each person on the last day of their infectious period before either recovery or death.

The timing of public health and physical distancing restrictions was set to match that observed in each country. For Australia, Day 0 was estimated to be January 16^{th}, 10 days prior to the first reported case (i.e incubation period for first case, plus three days for detection). For NZ, Day 0 was estimated to be February 16^{th}. Physical distancing policies were enacted in the model for Australia on day 72 (March 28^{th}) and for NZ on day 39 (March 26^{th}). In anticipation of the application of restrictions, people began physical distancing measures 14 days prior to policy implementation up to a maximum of 85% of people maintaining adequate separation to prevent transmission of the virus, 85% of the time. The increase in physical distancing behaviours prior to policy implementation followed a power-law determined by the number of days between the current day (e.g., t*i*– 14) and the day of implementation and is consistent with observed mobility trends in Australia and NZ[16] (see https://bit.ly/2XI3v3z for details of calibration). Table 1 provides a summary of the parameters and 'agent' characteristics. The decay in adherence to physical distancing over the 60 day period was applied in reverse, with the decay in adherence over time following a power-law determined by the number of days between the expected day the current public health response is removed (t_j) and the current day in each country (e.g., t*j* - t*i*). That is, as the day that restrictions being removed moved closer, people began reducing their levels of

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physical distancing in anticipation of this date, returning to baseline at day 60. A period of 60 days was selected in accordance with what we (and other policy analysts[17]) regard may be a likely maximal tolerance for politicians and the public to stay under strict distancing policies associated with minimising social, economic and health impacts of restrictions. Rates of adherence over time in each scenario are depicted in Figure 2.

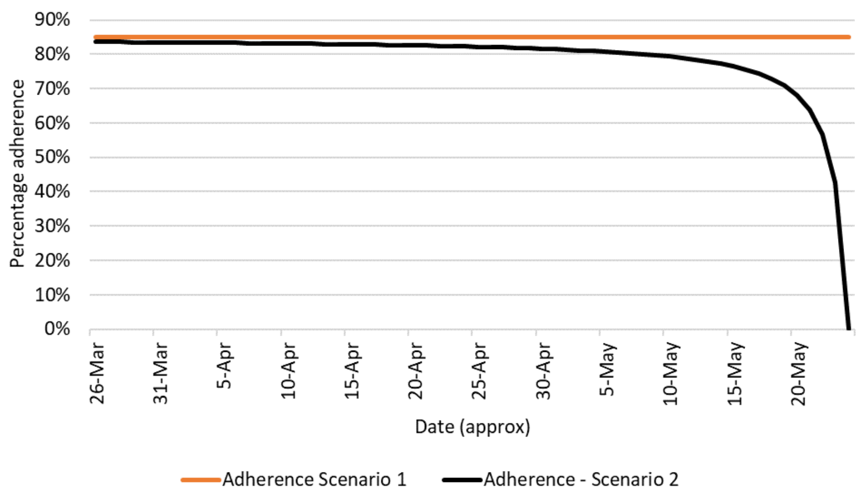

Figure 2. Percentage of public adherence to physical distancing restrictions over time under each scenario

The behaviour of simulated people in the model in response to the use of physical distancing restrictions was that where possible (i.e., 85% of the time), 85% of people avoided either being in, or moving to, locations occupied by other people. The remainder did not. The selection of people who actively avoided others was updated at each time-step (i.e., there were no high or low adherence individuals who always acted pro or anti-socially). Adherence resulted in a 'spreading-out' of people in the model environment, a reduction in movement, and a consequent reduction in the ability of people to transmit the virus. Under conditions of physical distancing, people only moved if others who did not observe distancing rules (e.g., through necessity or non-adherence) moved into the location they were currently occupying. In such circumstances, adherent people moved away by locating the closest currently unoccupied location in their surrounds.

To validate the ABM-SEIR model we ran both an unmitigated scenario and applied the SARS-CoV-2 data from Wuhan, Hubei Province, China. Details of the validation are reported in the on-line repository (https://bit.ly/2XI3v3z). Importantly, the reported ABM-SEIR model developed and reported here, reflects the disease trajectories as reported in the literature [13,14].

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Table 1. Parameter estimates and 'agent' characteristics used in the ABM-SEIR models

Key Parameters	Parameter Estimates (Australia)	Parameter Estimates (NZ)
Physical distancing (% of people limiting movement and maintaining a distance of 1.5m (Aus) or 2.0m (NZ) in public)	85%	85%
Physical distancing - time (% of time that people successfully maintain a distance of 1.5m (Aus) or 2.0m (NZ) in public)	85%	85%
Proportion of essential workers	30% of working age-people	30% of working age-people
Mean incubation period (days, log-normal)	m = 5, sd = 0.44	m = 5, sd = 0.44
Mean illness period (days, log-normal)	m = 15, sd = 0.99	m = 15, sd = 0.99
Mean adherence with isolation of infected cases (%, log-normal)	m = 0.95, sd = .01	m = 0.95, sd = .01
Super-spreaders as a proportion of population[¥]	10%	10%
Number of days after infection that new cases are publicly reported	8	8
Day of case 0 (Day 0)	January 16th, 2020	February 16th, 2020
Days from case 0 to policy enactment	72 (March 28th, 2020)	39 (March 26th, 2020)
Asymptomatic cases (% of people)	50%	50%
Infectivity of asymptomatic cases vs symptomatic cases	33%	33%
Physical distancing anticipation time-window	14 days	14 days
Decay in physical distancing adherence window	60 days (May 26th)	60 days (May 28th)
Symptomatic case identification (via testing and contact tracing), compliance with isolation	95%	95%
Target peak effective reproduction number (Rt) across model runs	2.2 – 2.7	2.2 – 2.7
Overseas case import: local case ratio	1:1	1:1

Agent Characteristics	Definition
Infection status	Infected, susceptible, recovered, deceased

Time now	The number of days (integer) since an infected person first became infected with SARS-CoV-2
Age-range	The age-bracket (categorical) of the person, calibrated to census data deciles from 0 to 100.
Risk of death	The overall risk of death (float) for this person based on their age-profile having experienced the disease – calibrated to international data
Location	The current location of the simulated person (agent) in the model interface
Pace	The speed at which the person moves around the environment – higher speeds resulted in more close contact with other people (agents) in the model
Heading	The direction of travel of the person at the current time-step. In conjunction with the scaling approach, the heading variable was used to create local communities and control interaction between and across communities
Contacts	A count (integer) of contacts the person (agent) had interacted with in the past day as they moved within the model's environment

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¥ 10% of the population transmit infections widely through frequent travel outside their local area

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Findings

At the time of writing (April 21st, 2020) there was a total of 6619 confirmed cases of SARS-CoV-2 in Australia, including a total of 71 deaths, 2361 current infections and 4258 recovered individuals. In NZ, these figures are 1113 confirmed cases (1440 confirmed and probable), 12 deaths, 466 current infections and 974 recovered individuals. Approximately 50% of reported cases in Australia and NZ originated from outside country borders, arriving by air and sea.

Australia: The findings from our ABM-SEIR model reflects the SARS-CoV-2 infection experience to April 20th in Australia. Although elimination is possible given Australia's current policy settings, it is delayed by virtue of Australia's deferred start to physical distancing restrictions from the date of identification of Case 0 (72 days), and hence the greater starting caseload prior to intervention. Nonetheless, the estimates from the model under consistent public adherence to current policy settings, suggest there is a 90% likelihood that Australia could eliminate SARS-CoV-2 from the population by July 10th (104 days post physical distancing implementation, 95% SI: June 30th to August 9th) (see Figure 5). The median estimated date for elimination under the adherence scenario is June 15th (95% SI: May 13th to July 30th). An 80% probability of elimination is achieved in Australia at 97 days post restrictions, on July 3rd (95% SI: June 29th to August 3rd). Statistics for the non-adherence scenario were not calculated due to the frequency of null values (i.e., trials where elimination did not occur by the end of the simulation).

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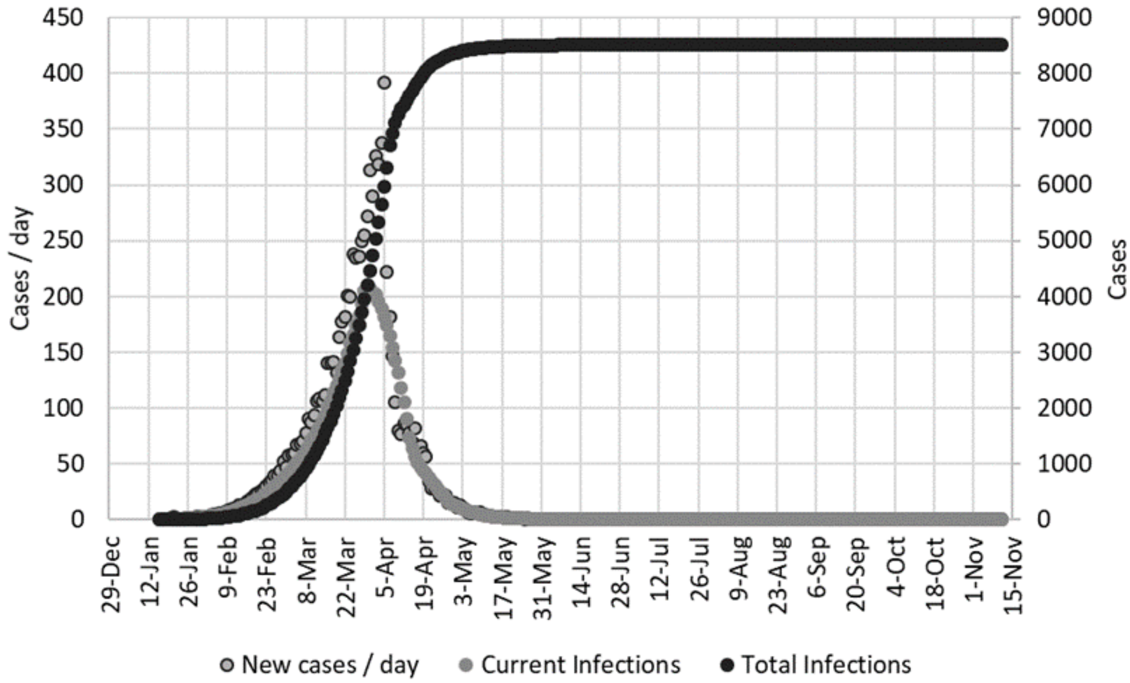

Figure 3. Estimated Australian disease progression under consistent adherence with physical distancing policies (average number of daily and cumulative cases from 1000 simulations)

Australia is less likely to eliminate SARS-CoV-2 from the population if adherence to current physical distancing policies decay over the 60-day intervention period (to May 28th) from a current estimated 85% during the onset of the 60-day implementation period (see Figure 2). We estimate there is only a 35% chance that Australia can eliminate SARS-CoV-2 under the decay in adherence scenario (see Figure 5).

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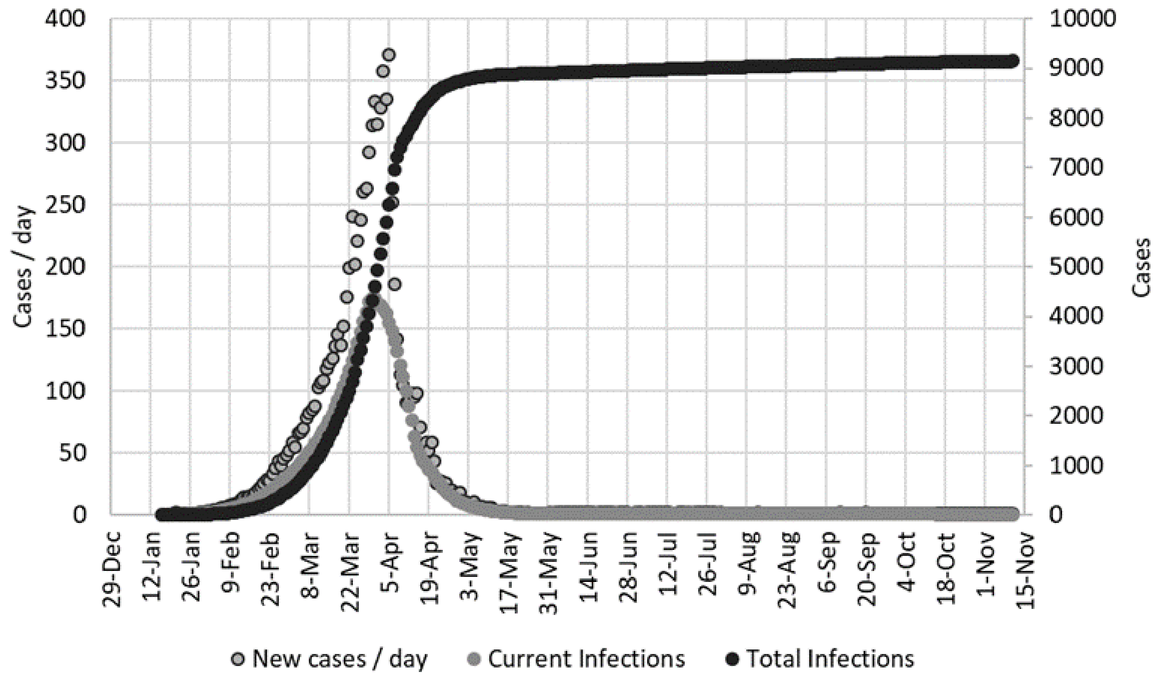

Figure 4. Estimated Australian disease progression with decay in adherence to physical distancing (average number of daily and cumulative cases from 1000 simulations).

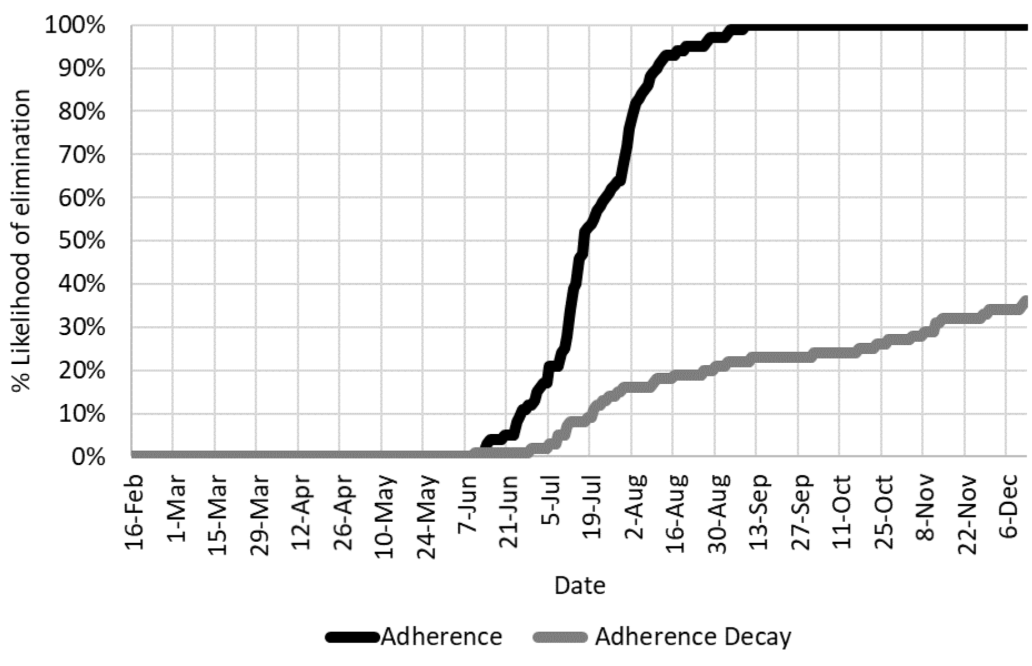

Figure 5. Estimated likelihood of disease elimination in Australia under conditions of i) adherence to physical distancing or ii) a decay in adherence

NZ: Results for NZ demonstrate a pattern of disease progression consistent with that observed and recorded between February 26th and April 20th, 2020[4]. Prior to implementation of the governments physical distancing policy on March 26th, growth in new cases appeared exponential, but flattened through to April 5th whereupon the pattern became one of sharp decline. The growth curve was exacerbated by a significant import of cases from outside NZ arriving via air[4]. This pattern is also reflected in our model's results, providing confidence that the representation of disease transfer between individuals, case import, and public health interventions such as physical distancing are adequately represented by the behaviour of the synthetic population.

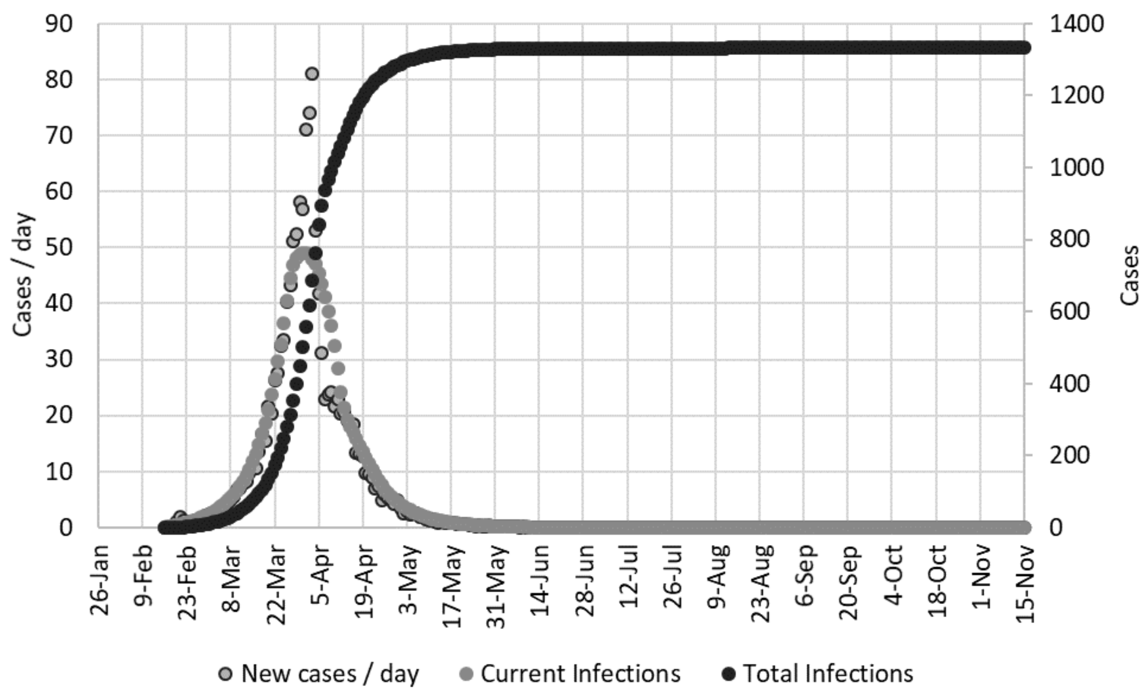

Figure 6. Estimated NZ disease progression under consistent adherence with physical distancing policies (average number of daily and cumulative cases from 1000 simulations)

Based on consistent application of, and adherence to, physical distancing policies associated with NZ's current strategy, we estimate there is a 90% probability of eliminating SARS-COV-2 in NZ by July 14th, 2020 (110 days post restrictions, 95% SI: 27th June to 16th September) (see Figure 8). An

80% likelihood of elimination is estimated at 98 days or July 2, post restrictions (95% SI: June 21st to August 1st). The median estimated date for elimination under the adherence scenario is June 17th (95% SI: interval May 28th to August 7th). Under conditions of gradual decay in adherence from 85% to 0% over the 60-days from implementation of restrictions to May 26th, we estimate that NZ is unlikely (36% chance) to achieve elimination (see Figures 7 and 8). A summary of findings for Australia and New Zealand is reported in Table 2.

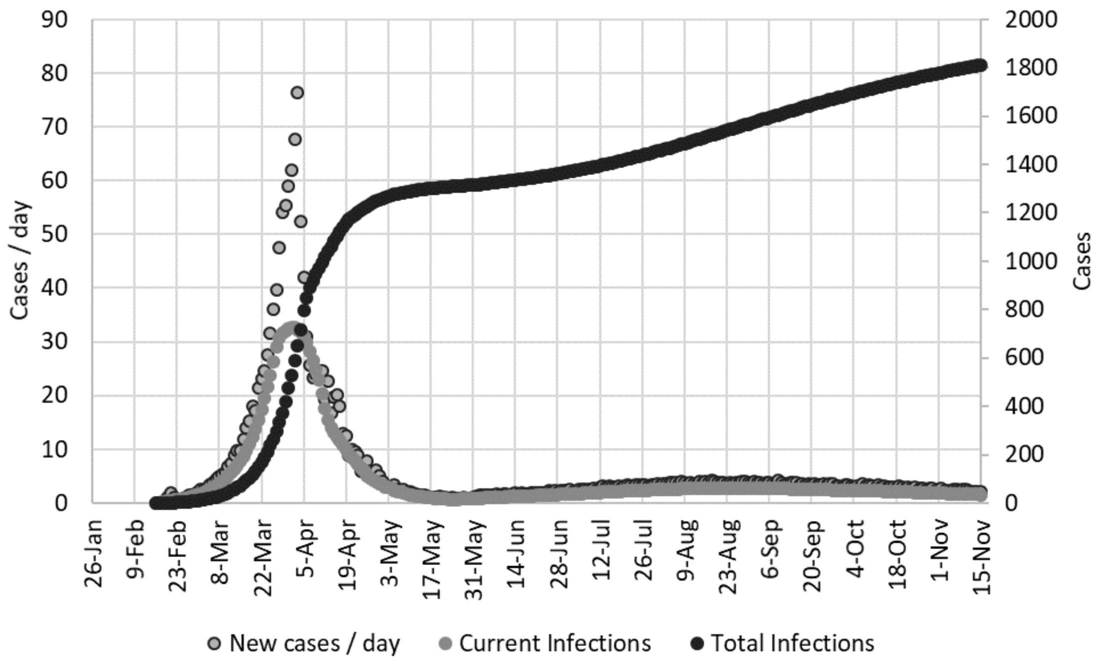

Figure 7. Estimated NZ disease progression with decay in adherence to physical distancing (average number of daily and cumulative cases from 1000 simulations)

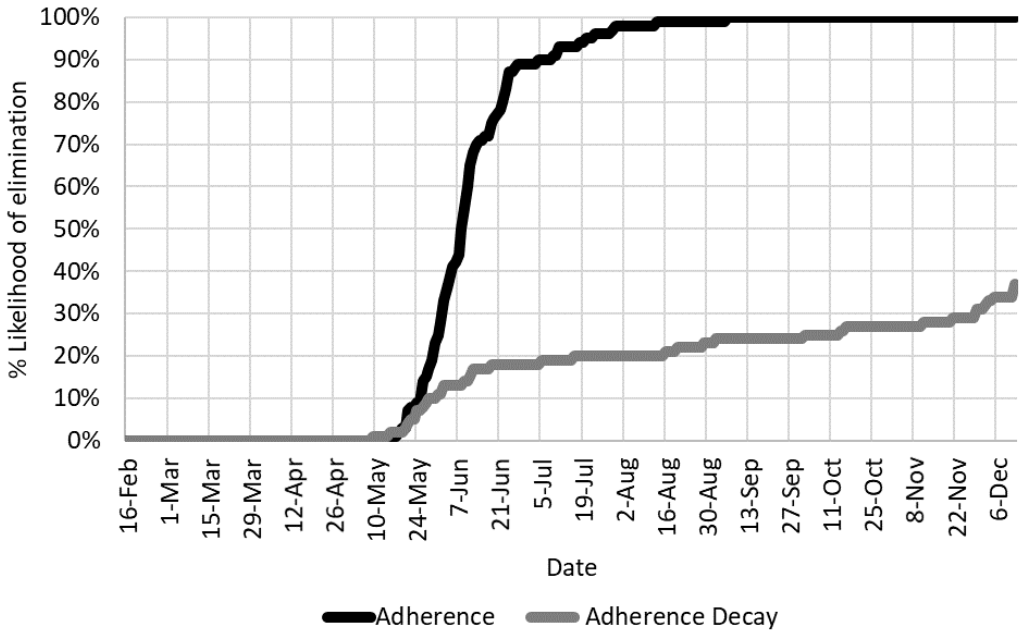

Figure 8. Estimated likelihood of disease elimination in NZ under conditions of either i) physical distancing or ii) decay in adherence to physical distancing

Table 2. Summary of findings for Australia and New Zealand using the ABM-SEIR

Scenario 1. Adherence condition	**Australia**	**NZ**
Median estimated elimination date	June 15th (95% SI May 13th to Jul 30th)	June 17th (95% SI May 28th to Aug 7th)
80% estimated probability of elimination	July 3rd (95% SI 73% - 91%)	July 2nd (95% SI 70% - 88%)
90% estimated probability of elimination	July 10th (95% SI 83%- 96%)	July 14th (95% SI 87% - 99%)
Scenario 2. Adherence decay condition		
Median estimated elimination date	Uncalculated* – 35% likelihood	Uncalculated* – 36% likelihood

80% estimated probability of elimination	nil	nil
90% estimated probability of elimination	nil	nil

*Figures cannot be calculated due to null values of elimination dates extending beyond the simulation time-window

Interpretation

These findings suggest that for island states such as Australia and NZ, the potential to eliminate the SARS-CoV-2 infection in a short-to-medium timeframe is high. Under maintained strong physical distancing, elimination is achieved with 90% probability by July 10th in Australia and July 14th in NZ. However, under our scenario of decaying adherence to physical distancing, a rebound in SARS-CoV-2 infections (i.e., a second wave) is likely in both countries, and at 100 days the probability of elimination is 18% in Australia and 16% in NZ.

Both NZ and Australia have similar potential to attain elimination of SARS-CoV-2 and hence the opportunity to return to some 'new normal' of social and economic activity (at levels determined by the government). However, our results indicate that the margin of error for both to achieve elimination is small. Marginal changes in general non-adherence with physical distancing and avoidance activities could see SARS-CoV-2 persist in the community for an extended duration. Still, it appears that for both countries the 'go hard, go early' policy position has expedited reduced transmission rates to this point. Both countries, however, now find themselves at critical policy junctures where decisions related to relaxation of measures (prior to late May) are being considered, with the short-term economic and health policies in potential conflict.

Our finding that island jurisdictions have the potential to eliminate SARS-CoV-2 is also reflected by the success observed in Taiwan. Taiwan acted at least 6-8 weeks before both Australia and NZ by imposing border controls on January 25th, 2020. An extensive public health response ensued including, the testing of individuals showing symptoms of SARS-CoV-2 (Taiwan has instituted one of the most comprehensive testing regimes per case of SARS-CoV-2)[18], isolating individuals (and their close contacts), extensive contact tracing and face masks whilst in public. For the past 10-

days, Taiwan has occasionally had zero new cases on some days, which suggests that they may be able to eliminate SARS-CoV-2 within a few weeks.

A limitation with this work is that it does not capture changes in hygiene behaviours (hand washing and cough etiquette) which may accelerate the speed of progress towards elimination. This is also the case for any widespread adoption of mask use (e.g., amongst essential workers) and ongoing developments in both countries around the expansion of testing (to identify new cases) and the likely advances in the use of digital technologies for rapid and more efficient contact tracing[19]. Further, although we modelled two scenarios of behavioural adherence over time, other patterns and timelines are also possible. For example, investigation of less drastic declines in physical distancing, combined with improved testing and contract tracing regimes, is a high priority for future simulations.

The evidence from Taiwan suggests that with early border restrictions and rigorous public health responses, elimination of SARS-CoV-2 is feasible whilst also maintaining levels of social and economic activity. Given the delayed border restrictions imposed in Australia and NZ, physical distancing strategies for prolonged periods are needed to achieve the goal of eliminating SARS-CoV-2.

With the likelihood of a viable vaccine some time away, and the prolonged burden on the health systems in pursuing a strategy of 'suppression', a public health response of 'elimination' is an important one to pursue in Australia as it appears to be in NZ and in Taiwan. Importantly, this study provides the potential timeframe needed to achieve elimination of the virus in Australia and NZ. Nevertheless, there are a multitude of factors each country must consider in addition to the probability of success of an elimination strategy. Such factors as the probability of re-entry of the virus after initial elimination (and the probability that any such outbreaks can be successfully controlled); the time to, and likelihood of, a vaccine or highly effective antivirals (the long-run success of the elimination strategy hinges on the eventual arrival of a vaccine); and the cost benefit ratio compared to other options particularly a strategy focused on suppression are needed.

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