

Will the Large-scale Vaccination Succeed in Containing the COVID-19 Epidemic and How Soon?

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The availability of vaccines provides a promising solution to containing the COVID-19 pandemic. Here, we develop an epidemiological model to quantitatively analyze and predict the epidemic dynamics of COVID-19 under vaccination. The model is applied to the daily released numbers of confirmed cases of Israel and United States of America to explore and predict the trend under vaccination based on their current epidemic status and intervention measures. For Israel, of which 53.83% of the population was fully vaccinated, under the current intensity of NPIs and vaccination scheme, the pandemic is predicted

to end between May 14, 2021 to May 16, 2021 depending on an immunity duration between 180 days and 365 days; Assuming no NPIs after March 24, 2021, the pandemic will ends later, between July 4, 2021 to August 26, 2021. For USA, if we assume the current vaccination rate (0.268% per day) and intensity of NPIs, the pandemic will end between February 3, 2022 and August 17, 2029 depending on an immunity duration between 180 days and 365 days. However, assuming an immunity duration of 180 days and with no NPIs, the pandemic will not end, and instead reach an equilibrium state with a proportion of the population remaining actively infected.

Overall the daily vaccination rate should be chosen according to the vaccine efficacy and the immunity duration to achieve herd immunity. In some situations, vaccination alone cannot stop the pandemic, and NPIs are necessary both to supplement vaccination and accelerate the end of the pandemic. Considering that vaccine efficacy and duration of immunity may be reduced for new mutant strains, it is necessary to remain cautiously optimistic about the prospect of the pandemic under vaccination.

1 Coronavirus disease 2019 (COVID-19) has rapidly spread to more than 200 countries and
2 territories since the first cases reported in Wuhan, China on 31 December 2019, and the pan-
3 demic is still ongoing. As of March 24, 2021, COVID-19 has resulted in more than 131 million
4 infections, causing around 2.85 million deaths. Given the high infectivity and limited clinically
5 effective medicine for COVID-19, a variety of non-pharmaceutical interventions (NPIs) were
6 implemented world-wide intending to diminish the viral transmission and outbreaks, such as
7 restrictions on movement, ban on the gatherings, social distancing, etc. The effectiveness of the
8 NPIs in mitigating the viral spread have been reported in previous studies (1–3).

9 Vaccines become the crucial solution to containing the pandemic. Currently over 200

10 SARS-CoV-2 vaccine candidates are under swift development with different technology, includ-
11 ing inactivated virus vaccines, live attenuated vaccines, recombinant protein vaccines, replication-
12 incompetent vector vaccines, replication-competent vector vaccines, inactivated virus vector
13 vaccines, DNA vaccines and RNA vaccines (4). Several candidates have completed the phase
14 III human clinical trials and efficacy testing (5). The announced efficacy of vaccines is 95% for
15 Pfizer/BioNTech (RNA vaccines) (6); 91.6% for Gamaleya (recombinant protein vaccines) (7);
16 94.1% for Moderna (RNA vaccines) (8); 70.4% for AstraZeneca (replication-incompetent vec-
17 tor vaccines) (9); 79.34% for Sinopharm (inactivated virus vaccines) (10); 50.65% ~ 91% for
18 Sinovac (inactivated virus vaccines) (11). The total capacity by 2021 is estimated to be around
19 7.4 billion doses (12), covering less than half of the global population (for most of COVID-19
20 vaccines 2 doses are required to get fully vaccinated). On December 14, 2020, UK became the
21 first country starting the vaccination scheme, and as of March 24, 2021, more than 80 countries
22 have started the vaccinations. Among these countries, Israel has the highest full vaccination
23 rate of 53.83%, and USA has the largest vaccination doses of 130.47 million.

24 Although the availability of vaccines is a remarkable step towards the ending of COVID-19
25 pandemic. The prospect of the pandemic control is still unclear. It is important to quantitatively
26 explore and predict the epidemic trend under the current speed of vaccination, vaccine efficacy
27 and the strength of NPIs. And even more important, is to explore and evaluate the optimal
28 scheme of vaccination. In this study, we develop an epidemic model to explore the pandemic
29 dynamics under vaccination and NPIs. We apply the model to analyze and predict the pandemic
30 trend of Israel and USA given their daily vaccination rates and other parameters, considering
31 Israel is a leading country in vaccination and USA has a much larger population size and with
32 the most severe COVID-19 pandemic. We also provide a formula for choosing speed of vac-
33 cination under different vaccine efficacy, immunity duration and NPIs. These results provide
34 insights on efficient COVID-19 epidemic control under vaccination.

35 **Model**

36 Based on our previous work SUQC (Susceptible -Unquarantined- Quarantined- Confirmed) (3),
37 we develop a new model, named SUVQC (Susceptible- Unquarantined- Vaccinated- Quarantined-
38 Confirmed), to describe the epidemic dynamics of COVID-19 under vaccination. SUVQC in-
39 cludes nine variables corresponding to different states of an individual from the population (Fig.
40 1):

41 $S(t)$, the number of susceptible individuals in the population at time t . For COVID-19, all
42 individuals are assumed to be susceptible to the disease, except for those gain immunity through
43 vaccination or infection. Note that the immunity against COVID-19 is not permanent, and an
44 infected or vaccinated person becomes susceptible again when it is beyond the protection period
45 of immunity.

46 $V(t)$, the number of fully vaccinated individuals at time t that are still actively under pro-
47 tection with immunity gained through vaccination.

48 $U(t)$, the number of infected individuals who are infectious and un-quarantined. $U(t)$ in-
49 cludes two groups: $U_S(t)$, who are un-quarantined infected individuals from susceptible indi-
50 viduals, and $U_V(t)$, who are from vaccinated individuals. $U(t) = U_S(t) + U_V(t)$. $U_V(t) > 0$ is
51 due to the fact that COVID-19 vaccines cannot provide 100% protection.

52 $Q(t)$, the number of quarantined infected individuals. The quarantined infected individuals
53 have no contact with susceptible and vaccinated individuals and thus cause no infection in the
54 population. Note that for simplicity, it also includes the infected individuals who have never
55 been quarantined and finally transfer their state to $Q(t)$ due to recovery and loss of infectivity.

56 $R_Q(t)$, the number of individuals among the quarantined, who were originally infected but
57 non-confirmed, and are currently recovered with active immunity to the virus.

58 $A(t)$, the number of confirmed infected cases who are still in active infection state, and are

59 not recovered or dead yet.

60 $R_c(t)$, the number of recovered individuals who were confirmed cases and are still immune
61 to the virus.

62 $D_c(t)$, the number of dead individuals among the confirmed infected cases.

63 Other than the above nine variables, we also define $C(t)$, the cumulative confirmed infected
64 cases. $\frac{dC(t)}{dt} = [\gamma_2 + (1 - \gamma_2)\sigma]Q(t)$.

65 The model includes 12 parameters:

66 t_s , the average duration of immunological memory of individuals who recover from infec-
67 tion.

68 t_v , the average duration of immunological memory of vaccinated individuals.

69 α , the infection rate, which is the average number of newly infected cases from S that is
70 caused by an un-quarantined infected in U_S per day.

71 $\eta(t)$, the daily number of individuals fully vaccinated.

72 λ_1 , the reduced probability for a vaccinated susceptible individual being infected. The **vac-**
73 **cine efficacy** is defined as $1 - \lambda_1$.

74 λ_2 , the reduced infectivity of vaccinated infected individual compared to U_s , that is, the
75 average infection rate of U_v is $\lambda_2\alpha$.

76 γ_1 , the quarantine rate for an un-quarantined infected being quarantined.

77 γ_2 , the confirmation rate of Q , is the probability that the quarantined infected are identified
78 to be confirmatory cases by a conventional method.

79 σ , the subsequent confirmation rate of those infected that are not confirmed by the conven-
80 tional methods, but confirmed with some additional tests.

81 k_1 , the ratio of un-confirmed infected cases over confirmed infected cases.

82 k_2 , the ratio of dead to recovered individuals among all confirmed cases.

83 γ_3 , the recovery rate of active confirmed infected individuals.

84 The transition among different states during the epidemic dynamics is summarized in Equa-
85 tion 1, and demonstrated in Fig. 1. The susceptible individuals S become V after vaccination at
86 a constant rate. S can also move to U_s due to infection. Similarly, the vaccinated individuals V
87 still have some chance of getting infected, and thus transit to U_v . The infected individuals U_s and
88 U_v move to Q by quarantine measures and lose the infectivity. Among individuals in Q state,
89 some are confirmed, and later become recovered or dead. The rest individuals of Q are not con-
90 firmed by tests or other approaches, and move to R_Q directly. Note that the $Q \rightarrow R_Q$ flow may
91 be due to the lack of test kits, or the infected cases with no symptoms (asymptomatic infection).
92 It is reasonable to assume that all individuals without being confirmed are with mild symptoms,
93 and thus no flow of $Q \rightarrow D_Q$ directly. Individuals from V , R_c and R_Q finally become suscep-
94 tible to the disease again after a period of time, since the immunity against COVID-19 is likely
95 not permanent. Since we are unable to distinguish between un-vaccinated individuals in R_Q and
96 S at time t , $\eta(t)$ includes two parts: $k_3\eta(t)$ individuals transiting from S to V , and $(1 - k_3)\eta(t)$
97 individuals transiting from R_Q to V , where $k_3 = \frac{S(t)}{S(t)+R_Q(t)S(t)/(S(t)+\lambda_1 V(t))}$.

$$\left\{ \begin{array}{l}
 \frac{dS(t)}{dt} = -\alpha \frac{U_S(t)S(t)}{N(t)} - \lambda_2 \alpha \frac{U_V(t)S(t)}{N(t)} - k_3 \eta(t) + \frac{1}{t_v} V(t) + \frac{1}{t_s} (R_C(t) + R_Q(t)) \\
 \frac{dV(t)}{dt} = -\lambda_1 \alpha \frac{U_S(t)V(t)}{N(t)} - \lambda_1 \lambda_2 \alpha \frac{U_V(t)V(t)}{N(t)} + \eta(t) - \frac{1}{t_v} V(t) \\
 \frac{dU_S(t)}{dt} = \alpha \frac{U_S(t)S(t)}{N(t)} + \lambda_2 \alpha \frac{U_V(t)S(t)}{N(t)} - \gamma_1 U_S(t) \\
 \frac{dU_V(t)}{dt} = \lambda_1 \alpha \frac{U_S(t)V(t)}{N(t)} + \lambda_1 \lambda_2 \alpha \frac{U_V(t)V(t)}{N(t)} - \gamma_1 U_V(t) \\
 \frac{dQ(t)}{dt} = \gamma_1 (U_S(t) + U_V(t)) - [\gamma_2 + (1 - \gamma_2)\sigma] Q(t) - k_1 [\gamma_2 + (1 - \gamma_2)\sigma] Q(t) \\
 \frac{dR_Q(t)}{dt} = k_1 [\gamma_2 + (1 - \gamma_2)\sigma] Q(t) - \frac{1}{t_s} R_Q(t) - (1 - k_3) \eta(t) \\
 \frac{dA(t)}{dt} = [\gamma_2 + (1 - \gamma_2)\sigma] Q(t) - \gamma_3 A(t) - k_2 \gamma_3 A(t) \\
 \frac{dR_C(t)}{dt} = \gamma_3 A(t) - \frac{1}{t_s} R_C(t) \\
 \frac{dD_C(t)}{dt} = k_2 \gamma_3 A(t) \\
 \frac{dC(t)}{dt} = [\gamma_2 + (1 - \gamma_2)\sigma] Q(t)
 \end{array} \right. \quad (1)$$

98 Parameter Inference

99 The observed data we can use in the modeling fitting is the series of numbers of daily reported
 100 infected cases. Since the SUVQC model includes multiple parameters, for most of which, the
 101 data provides very limited information, we thus infer nine parameters and the initial values
 102 of eight variables using information from other sources, including known facts and previous
 103 studies:

- 104 • t_s and t_v : A recent study demonstrated that the immune memory caused by SARS-CoV-2
 105 infection can last up to 8 months after infection (13). Several other studies also suggested
 106 an immunization period of at least 6-9 months (14–16). At present, there is no clear

107 conclusion on how long the immune protection induced by the vaccine can last. We set
108 it to $t_s = t_v = 240$ days. Since the duration of immunity is critical to the epidemic
109 dynamics, we also try three different durations of immunity, including 90 days, 180 days
110 and 365 days.

111 • $\alpha = 0.2967$: obtained by fitting an exponential curve to the numbers of confirmed cases
112 in Wuhan in the very early phase of the pandemic (3).

113 • λ_1 and λ_2 : the vaccines used so far in Israel and USA are Pfizer/BioNTech and Moderna,
114 with the efficacy of 95% and 94.1% respectively (6, 8). Thus we set $\lambda_1 = 0.95$. No epi-
115 demic data is available for estimating λ_2 yet. It is reported that vaccines can reduce the
116 incidence of severe illness, which may imply lower infectivity of U_v than U_s . Neverthe-
117 less, even the asymptomatic patients have similar viral load to that in the symptomatic
118 patients (17). Thus we assume U_v has the same infectivity as U_s and set $\lambda_2 = 1$.

119 • γ_3 : the recovery rate of active confirmed cases is set to be $\gamma_3 = 1/14$, since the mean
120 hospital admission days for survivors and non-survivors are 11.3 days and 14.5 days re-
121 spectively according to former studies (18).

122 The values of some other parameters and variables, e.g., k_1 , k_2 , η , V_0 , and $R_C(0)$ are
123 population-specific, and will be elaborated in following sections.

124 $U_s(0)$, the initial number of un-quarantined infected individuals from susceptible individ-
125 uals, $Q(0)$, the initial number of quarantined infected individuals, and parameters γ_1 , $\beta =$
126 $\gamma_2 + (1 - \gamma_2)\sigma$ are inferred by fitting the numbers of daily reported cumulative confirmed cases
127 $C(t)$ with the SUVQC model. The loss function is defined as (3),

$$err(\gamma_1, \beta, U_0^s, Q_0) = \|\mathbf{C} - \hat{\mathbf{C}}\|_2. \quad (2)$$

128 where $\hat{C} = f(\gamma_1, \beta, U_0^s, Q_0)$ is the expected cumulative confirmed case numbers from the model
129 (Eqn 1), which is solved by the fourth order Runge-Kutta method. The values of the four pa-
130 rameters or variables are inferred by optimizing the loss function with the interior-point method
131 (implemented with `fmincon` in MATLAB).

132 **The epidemic trend of Israel under vaccination**

133 The population size of Israel is around 9.05 million. The COVID-19 pandemic in Israel started
134 on February 21, 2020. The country has undergone three waves of outbreaks (see https://en.wikipedia.org/wiki/COVID-19_pandemic_in_Israel). We inferred the temporal dynamics of R_t as a function of time by
135 applying the SUQC model to daily reported confirmed cases using the sliding window scheme
136 (with a window size of 3 weeks and a step size of one week; blue curve, fig. S1). It demonstrates
137 the development and fluctuation of the pandemic during the process, being consistent with the
138 public reports. The Israel government issued a series of control measures during the period,
139 including social distancing, home isolation, travel bans, and restriction in movements etc. The
140 Government Stringency Index provided by OxCGRT (19, 20) couples well with the $R(t)$ trend,
141 indicating the efficiency of multiple intervention measures (red curve, fig. S1). As of March
142 24, 2021, 830,028 individuals have been reported to be infected by COVID-19. The
143 Israel government procured COVID-19 vaccines from multiple sources: 8 million shots from
144 Pfizer; 10 millions doses from AstraZeneca; and 6 million doses from Moderna. Vaccination
145 has started since December 19, 2020, and is progressing steadily and rapidly. As of March
146 24, 2021, around 53.83% of the Israel population has been fully vaccinated. Together with
147 other measures, vaccination demonstrates its efficiency, and the new confirmed cases demon-
148 strated a persistent downward trend since Jan 20, 2021. We analyze the epidemic dynamics
149 of COVID-19 in Israel under vaccination, and predict its future trend with the SUVQC model
150 under parameter settings inferred from the reported data up to March 24, 2021. The prediction
151

152 of future trend starts from March 24, 2021.

153 Some population-specific parameters and variables are inferred beforehand with prior knowl-
154 edge:

- 155 1. The proportion of infected individuals remaining asymptomatic throughout infection is
156 chosen to be 31% according to former studies (21), that is, $k_1 = 0.31/(1 - 0.31) = 0.45$;
- 157 2. $\eta = 54,753$ (0.605% of population), the number of daily vaccinated individuals is esti-
158 mated as the average of numbers from 30 days (2021-2-23 to 2021-3-24) according to
159 data from ourworldindata website (<https://ourworldindata.org/>). Note that $V(t)$ is defined
160 as the number of fully vaccinated individuals, and η is the daily number of individuals of
161 fully vaccinated. This is a simplification of the reality since individuals not fully vacci-
162 nated are also immune to COVID-19 in a lower efficacy;
- 163 3. $V_0 = 3,158,669$, the number of initial fully vaccinated individuals at Feb 23, 2021, is
164 adopted from ourworldindata website (<https://ourworldindata.org/>).
- 165 4. $k_2 = 0.74\%$, the ratio of dead and recovered individuals among confirmed cases, $C(0) =$
166 $759,572$, the initial confirmed cases, $D_C(0) = 5,634$, the initial confirmed deaths, and
167 $A(0) = 41,610$ are adopted from Johns Hopkins University Coronavirus Center (22).
- 168 5. $R_C(0) = 756,439$, the number of initial confirmed recovered individuals that still stain
169 immunological memory to the virus is estimated by the recurrence formula $R_C(t) =$
170 $(C(t) - R_C(t - 1))/t_s$. $R_Q(0)$ is calculated by $R_Q(0) = k_1 R_C(0)$.

171 Some other parameters, including $t_s = 240$ days, $t_v = 240$ days, $\alpha = 0.2967$, $\lambda_1 = 0.05$,
172 $\lambda_2 = 1$, $\gamma_3 = 1/14$ are universal across different countries and chosen according to section
173 "Parameter Inference".

174 We set $U_V(0) = 0$, since $V(t) \rightarrow U_V(t)$ is small compared to $S(t) \rightarrow U_S(t)$ at the early
175 stage of the vaccination. The initial number of un-quarantined infected individuals from sus-
176 ceptible individuals $U_s(0)$, the initial number of quarantined infected individuals $Q(0)$, and
177 parameters γ_1 , $\beta = \gamma_2 + (1 - \gamma_2)\sigma$ are inferred by fitting the numbers of daily reported cumula-
178 tive confirmed cases $C(t)$ with the SUVQC model. After obtaining all the values of parameters
179 and initial variables, the initial value of susceptible individuals in the population $S(0)$ is calcu-
180 lated with $S(0) = N - V(0) - U_S(0) - U_V(0) - Q(0) - R_Q(0) - A(0) - R_C(0) - D_C(0)$. We
181 explore the trends for two scenarios: one with NPIs, for which we assume the current control
182 measures will continue with the same intensity; the other without NPIs, for which we assume
183 that no more NPIs are imposed when under vaccination.

184 Fig. 2 presents the inference and prediction of epidemic dynamics in Israel assuming an
185 eight-month duration of immunological memory. The SUVQC model is fitted to the daily
186 numbers of confirmed cases from February 23, 2021 to March 24, 2021, and the unknown
187 parameters and variables are inferred to be $U_s(0) = 38,835$, $Q(0) = 26,736$, $\gamma_1 = 0.2714$
188 and $\beta = 0.0983$. The model fits well with the observed data (Fig. 2A, red points, $R^2 =$
189 0.9991). If we assume the intensity of NPIs remains as that of between February 23, 2021 and
190 March 24, 2021 (the corresponding mean Government Stringency Index of 56.82 by OxCGRT.
191 For comparison, the maximum Government Stringency Index of Israel is 94.44 around mid
192 April, 2020, and 68.33 between March 1, 2020 and March 24, 2021), the epidemic in Israel is
193 estimated to end around May 15, 2021 (with zero new confirmed case as the criterion), with
194 836,059 cumulative confirmed infected cases and 6,495 confirmed deaths. The number of
195 active cases ($A(t)$) is estimated to reach peak at Mar 5, 2021, with the maximum value of
196 $A(t) = 46,629$ (Fig. 2, A and B).

197 For the scenario assuming no more NPIs after March 24, 2021, the epidemic in Israel is
198 estimated to end around July 24, 2021, with 838,632 cumulative confirmed infected cases and

199 6,520 confirmed deaths. The number of active cases is estimated to peak on March 24, 2021,
 200 with the value of $A(t) = 27,356$ (Fig. 2, C and D).

201 To assess the impact of immunity duration of vaccines, we also carry out the same analysis
 202 with other possible t_s values, e.g., $t_s = t_v = 90, 180, 365$ days. The results are summarized
 203 in Table 1 (see the corresponding plots in Fig. S3-S5). Assume that maintaining the same
 204 intensity of NPIs as that of between February 23, 2021 and March 24, 2021, the epidemic in
 205 Israel will end between May 14, 2021 and May 19, 2021, depending on different durations
 206 of immunity. The number of cumulative confirmed infected cases is estimated to be between
 207 835,944 and 836,576, with the number of deaths between 6,493 and 6,500. The epidemic
 208 in Israel is estimated to last for much longer time if no NPI after March 24, 2021, ranging
 209 from July 4, 2021 to August 26, 2021, with the number of cumulative confirmed infected cases
 210 between 837,656 and 840,383, and the number of deaths between 6,513 and 6,533. However,
 211 the epidemic in Israel will never end if the duration of immunity is only 90 days and with
 212 no NPIs. After several waves of fluctuations, the epidemic reaches an equilibrium state, with
 213 68,742 active infected cases (Fig. 2, C and D, Table 1). The vibrations are due to the initial
 214 proportions of vaccinated individuals and susceptible individuals. Overall, the epidemic trend
 215 of Israel under vaccination is optimistic if the duration of immunity is longer than 6 months.

Table 1: Prediction of the epidemic in Israel with different durations of immunity

Duration of immunity	90 days	180 days	240 days	365 days
with NPIs				
Ending time	2021-5-19	2021-5-16	2021-5-15	2021-5-14
Infected number	836,576	836,169	836,059	835,944
216 Death number	6,500	6,496	6,495	6,493
Maximum active number	46,658	46,636	46,629	46,623
Date of maximum active number	2021-3-5	2021-3-5	2021-3-5	2021-3-5
Equilibrium value of active number	0	0	0	0
without NPI after Mar 24, 2021				

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	90 days	180 days	240 days	365 days
Duration of immunity				
Ending time	-	2021-8-26	2021-7-24	2021-7-4
Infected number	-	840,383	838,632	837,656
217 Death number	-	6,533	6,520	6,513
Maximum active number	125,593	27,368	27,356	27,343
Date of maximum active number	2021-11-30	2021-3-24	2021-3-24	2021-3-24
Equilibrium value of active number	68,742	0	0	0

218 **The trend of epidemic in United States of America under vac-** 219 **ination**

220 The population size of USA is around 327 million. The COVID-19 pandemic in US started
 221 around late January, 2020. The temporal dynamics of $R(t)$ of USA is also inferred by applying
 222 the SUQC model to the daily reported confirmed cases with a sliding window scheme (with
 223 a window size of 3 weeks and a step size of one week; blue curve, Fig. S2). From the $R(t)$
 224 curve, we similarly identify three waves of outbreaks: the early stage before early April, from
 225 June 6 to August 8, and from early-October to late-December. The Government Stringency
 226 Index provided by OxCGRT (19) (20) couples well with the $R(t)$ trend, which demonstrates
 227 the fluctuation of pandemic is highly correlated with the public events and implementation
 228 of controls by federal and state governments (red curve, fig. S2). As of March 24, 2021,
 229 30,012,522 confirmed infected cases have been reported. The USA government ordered 600
 230 million shots from Pfizer and Moderna, and before the end of July 2021, each company is
 231 expected to deliver 300 million doses in regular increments. Vaccination in USA has started
 232 since December 14, 2020. As of March 24, 2021, around 13.86% of the USA population have
 233 been fully vaccinated.

234 We also infer some parameters and variables before model-fitting with prior knowledge:

- 235 1. As of mid November 2020, 14.3% of the US population (around 47 million) were esti-
 236 mated to be infected by SARS-CoV-2 (23), and at the same time, the reported confirmed

237 cases is around 11 million. Thus $k_1 = (47 - 11)/11 = 3.3$ for USA.

238 2. $\eta = 876,824$ (0.268% of population), the number of daily vaccinated individuals is esti-
239 mated as the average of daily numbers of 30 days (February 23, 2021 to March 24, 2021)
240 from the ourworldindata website (<https://ourworldindata.org/>).

241 3. $V_0 = 19,882,544$, the number of initial fully-vaccinated individuals on February 23,
242 2021, is adopted from the ourworldindata website (<https://ourworldindata.org/>).

243 4. $k_2 = 1.82\%$, the ratio of dead and recovered individuals among confirmed cases, $C(0) =$
244 $28,302,207$, the initial confirmed cases, $D_c(0) = 503,937$, the initial confirmed deaths,
245 and $A(0) = 9,196,400$ are adopted from Johns Hopkins University Coronavirus Center
246 (22).

247 5. $R_C(0) = 28,185,069$, the number of initial confirmed recovered individuals that still
248 remain immunity to the virus is estimated with the recurrence formula $R_C(t) = (C(t) -$
249 $R_C(t - 1))/t_s$. $R_Q(0)$ is calculated with $R_Q(0) = k_1 R_C(0)$.

250 Fig. 3 presents the prediction and inference of the epidemic in USA assuming a 8-month
251 duration of immunity. The SUVQC model is fitted to the daily numbers of confirmed cases
252 from February 23, 2021 to March 24, 2021, and the unknown parameters and variables are
253 inferred to be $U_s(0) = 1,590,637$, $Q(0) = 747,060$, $\gamma_1 = 0.1603$ and $\beta = 0.1230$ (Fig. 3A,
254 red points, $R^2 = 0.9997$). Suppose that all the inferred parameters remain constant values in
255 future and the level of NPIs is retained similar to that of between February 23, 2021 and March
256 24, 2021 (the mean of the Government Stringency Index is 63.50 by OxCGRT. In comparison,
257 the maximum Government Stringency Index of US is 75.46 in late November, 2020, and 65.91
258 between March 1, 2020 and March 24, 2021). The ending time of the epidemic of USA is
259 estimated to be September 1, 2022, with 34,672,274 confirmed infected cases and 782,183

260 confirmed deaths (Fig. 3, A and B). However, if we assume no NPIs with other parameters
261 remain the same, the epidemic will end much later at February 28, 2027, with 62,782,387
262 confirmed infected cases and 1,284,642 confirmed deaths (Fig. 3, C and D). Notably that given
263 a limit duration of immunity of 3-6 months, and the speed of vaccination, there is a probability
264 that the epidemic never end without NPIs (Table 2, see the corresponding plots in Fig. 3, 5, and
265 fig. S6, S7).

266 We thus explore the epidemic dynamics in USA under other scenarios with different immu-
267 nity durations and a higher speed of vaccination (Table 3). With the accelerated vaccination rate
268 of $1\%N$ per day (around 4 times of the current vaccination rate) and with NPIs, the ending time
269 of the epidemic in USA ranges between July 23, 2021 and September 24, 2021, corresponding
270 to different immunity durations of 3, 6, 8 and 12 months (see the corresponding plots in Fig. 3,
271 and fig. S8-S10). The number of cumulative confirmed infections is estimated to be between
272 31,442,008 and 32,702,833, and the number of deaths between 724,434 and 746,979. The
273 epidemic in USA will last for much longer time if no NPIs after Mar 24, 2021, ranging between
274 September 2, 2021 and January 20, 2022, with the number of cumulative confirmed infections
275 between 32,575,585 and 43,588,222, and the number of deaths between 744,704 and 941,552.

276 Significantly, assuming an immunity duration of three months and the current daily vacci-
277 nation rate of $\eta = 0.268\%N$ per day, the epidemic in USA will never end (Table 2 and Fig.
278 5). The epidemic reaches an equilibrium state with 2,276,581 active infected cases if under the
279 current intensity of NPIs, and an equilibrium state of 4,453,576 active infected cases without
280 NPI.

Table 2: Prediction of the epidemic in USA with different durations of immunity

281

Duration of immunity	90 days	180 days	240 days	365 days
with NPIs				
Ending time	-	2029-8-17	2022-9-1	2022-2-3
Infected number	-	43,635,623	34,672,274	32,908,322
Death number	-	942,400	782,183	750,653
Maximum active number	9,196,400	9,196,400	9,196,400	9,196,400
Date of maximum active number	2021-2-23	2021-2-23	2021-2-23	2021-2-23
Equilibrium value of active number	2,276,581	0	0	0
without NPI after Mar 24, 2021				
Ending time	-	-	2027-2-28	2022-7-21
Infected number	-	-	62,782,387	44,675,741
Death number	-	-	1,284,642	960,991
Maximum active number	8,842,884	4,037,235	2,715,289	1,785,177
Date of maximum active number	2021-6-11	2021-6-25	2021-6-26	2021-3-24
Equilibrium value of active number	4,453,576	1,213,567	0	0

Table 3: Prediction of the epidemic in USA with different durations of immunity and accelerated vaccination of 1% N per day

Duration of immunity	90 days	180 days	240 days	365 days
with NPIs				
Ending time	2021-9-24	2021-8-6	2021-7-29	2021-7-23
Infected number	32,702,833	31,767,383	31,597,332	31,442,008
Death number	746,979	730,252	727,211	724,434
Maximum active number	1,792,512	1,787,972	1,786,647	1,785,177
Date of maximum active number	2021-3-24	2021-3-24	2021-3-24	2021-3-24
Equilibrium value of active number	0	0	0	0
without NPI after Mar 24, 2021				
Ending time	2022-1-20	2021-9-25	2021-9-13	2021-9-2
Infected number	43,588,222	34,194,285	33,261,982	32,575,585
Death number	941,552	773,638	756,973	744,704
Maximum active number	2146,505	1,787,972	1,786,647	1,785,177
Date of maximum active number	2021-5-28	2021-3-24	2021-3-24	2021-3-24
Equilibrium value of active number	0	0	0	0

284 **Formula for optimal design of vaccination to achieve herd im-** 285 **munity**

286 Let f be the proportion of the population that retains immunological memory by vaccina-
287 tion at time t , $f = V/N$. We consider a discrete transmission model for simplicity, with
288 t_i denote the i -th transmission cycle. Let $M(t_i)$ denote the number of new infected cases
289 at time t_i , it includes two parts: the un-quarantined infected individuals from vaccinated in-
290 dividuals, $U_v(t_i) = M(t_i)f\lambda_1/(f\lambda_1 + (1 - f))$, and from susceptible individuals $U_s(t_i) =$
291 $M(t_i)(1 - f)/(f\lambda_1 + (1 - f))$. The number of new infected cases at the next time step t_{i+1} is

$$M(t_{i+1}) = U_v(t_i)\lambda_2 R_0(f\lambda_1 + (1 - f)) + U_s(t_i)R_0(f\lambda_1 + (1 - f)). \quad (3)$$

292 By definition the effective reproductive number of time t_i can be calculated with

$$R(t_i) = \frac{M(t_{i+1})}{M(t_i)} = R_0(\lambda_1\lambda_2 f + 1 - f). \quad (4)$$

293 For an effective control of the epidemic, we should have $R(t_i) < 1$, which is

$$f > \frac{1 - 1/R_0}{1 - \lambda_1\lambda_2}, \quad (5)$$

294 and it is straightforward to get the speed of vaccination

$$\eta/N > \frac{1 - 1/R_0}{t_v(1 - \lambda_1\lambda_2)}. \quad (6)$$

295 Note when $V(t_i) = N$, the maximum value of $\eta(t_{i+1})/N = 1/t_v$, which implies that the
296 long-term upper bound of η/N is $1/t_v$. Thus from Eqn 6, we conclude that when $1 - 1/R_0 >$
297 $1 - \lambda_1\lambda_2$, the epidemic can not be terminated by vaccination solely. For example, assume that
298 the basic reproductive number of SARS-CoV-2 is $R_0 = 2.5$, and that U_v has the same infectivity
299 as U_s (that is, $\lambda_2 = 1$), λ_1 should be smaller than 0.4 (correspondingly, the efficacy of vaccine
300 is ≥ 0.6) to ensure ending the epidemic by vaccination only.

301 Equation 6 provides a useful formula for choosing vaccination rate taking into account of
302 the different values of R_0 , t_v and λ_1 to guarantee ending the epidemic. For $R_0 = 2.5$, $t_v = 100$
303 days, $\lambda_1 = 0.4$ (e.g., the efficacy of the vaccines 0.6), $\lambda_2 = 1$, η should be $> 1\%$ of the
304 population per day. For $R_0 = 2.5$, $t_v = 100$ days, $\lambda_1 = 0.05$ (e.g., the efficacy of the vaccines
305 0.95), $\lambda_2 = 1$, η should $> 0.63\%$ of the population per day (Fig. 6, red point). Fig. 6 provides
306 a thorough demonstration of the minimum vaccination rates to assure effectively ending the
307 epidemic for a wide range of R_0 and vaccine efficacy values.

308 Discussion

309 In this study, we develop a model SUVQC to characterize the pandemic dynamics of COVID-
310 19 under vaccination and NPIs. In addition to the intrinsic parameters of the epidemic, such
311 as transmissibility, and the effect of NPIs, the model also explicitly parameterizes multiple
312 key factors related to vaccination, including the vaccine efficacy, the vaccination rate, and the
313 reduced infectivity of individuals who have been vaccinated and infected etc.

314 Note that SUVQC has some strong assumptions, which may bias the inference and predic-
315 tion. The model assumes that all individuals are equally susceptible in the epidemic. In reality,
316 individuals in the hot spots of human interaction network are in a higher exposure risk level. A
317 vaccination program prioritizing these individuals are more effective to contain the epidemic,
318 especially when there is a shortage of vaccines. For such a vaccination program, the daily
319 vaccination rate provided by Eqn 6 can be overestimated. Furthermore, the model includes 12
320 parameters, for most of which the data (daily reported number of confirmed cases) is uninfor-
321 mative, and has to be inferred beforehand with prior knowledge. Some critical parameters, such
322 as the duration of effective immunity, is still unclear with limited studies. The prediction of
323 epidemic by the model are made based on some pre-selected values.

324 The model is applied to the numbers of daily reported confirmed cases to project the fu-

325 ture trends of Israel and USA with the parameters inferred based on their current epidemic
326 status and intervention measures. The analysis demonstrates that a high vaccine efficacy and
327 a high vaccination rate coupled with intensive NPIs can eliminate the spread of the virus very
328 efficiently. Although for USA, under some parameter settings, such as, a short duration of
329 immunity, or with no NPIs, the epidemic will not end and instead reach an equilibrium state
330 with a proportion of the population remaining actively infected. We further provide a unified
331 formula for determining the minimum daily vaccination rate for different values of effective
332 reproductive number and vaccine efficacy. Considering the vaccine parameters and epidemic
333 parameters are difficult to adjust in operation, a practical scheme is to supplement with NPIs
334 when implementing the vaccination plan.

335 However, there are many reasons to be conservative about the efficacy of vaccination in
336 suppressing the epidemics. The SARS-CoV-2 genomes are still actively evolving under selec-
337 tion with new mutations, and SARS-CoV-2 may gain function to partially escape the vaccine-
338 induced immunity and reduce the vaccine efficacy (24–28). It is possible that current vaccines
339 may have reduced efficacy and immunity duration in the near future. In addition, many COVID-
340 19 reinfection reports imply the immunity may not so strong and long-lasting (29,30). Excessive
341 optimism is undesirable considering the unpredictable factors. Retaining NPIs at least in some
342 extent is still necessary to contain the pandemic. If the vaccination program works, the pan-
343 demic in Israel should end by mid-May (no later than August 26, 2021, assuming there is no
344 NPIs and the duration of immunity is 180 days). If the does not end by then, we must re-evaluate
345 the role of vaccination.

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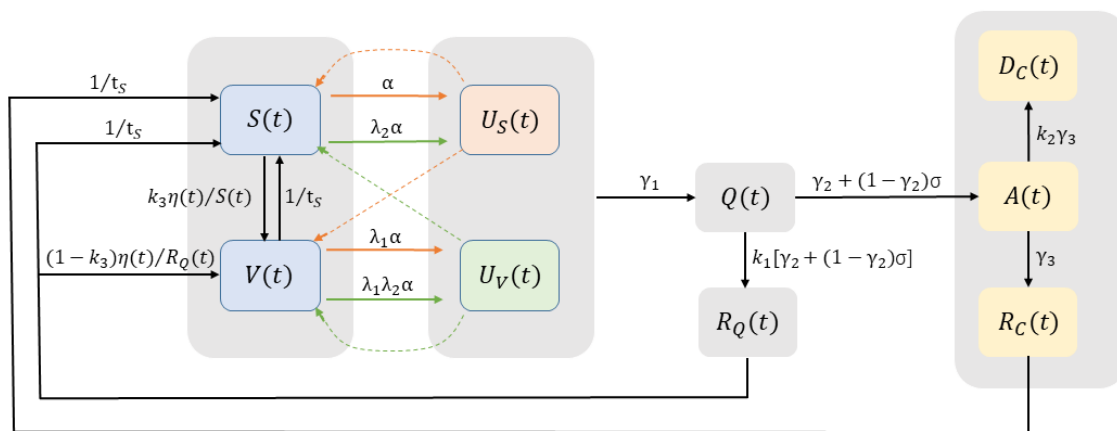


Figure 1: An schematic illustration of the model.

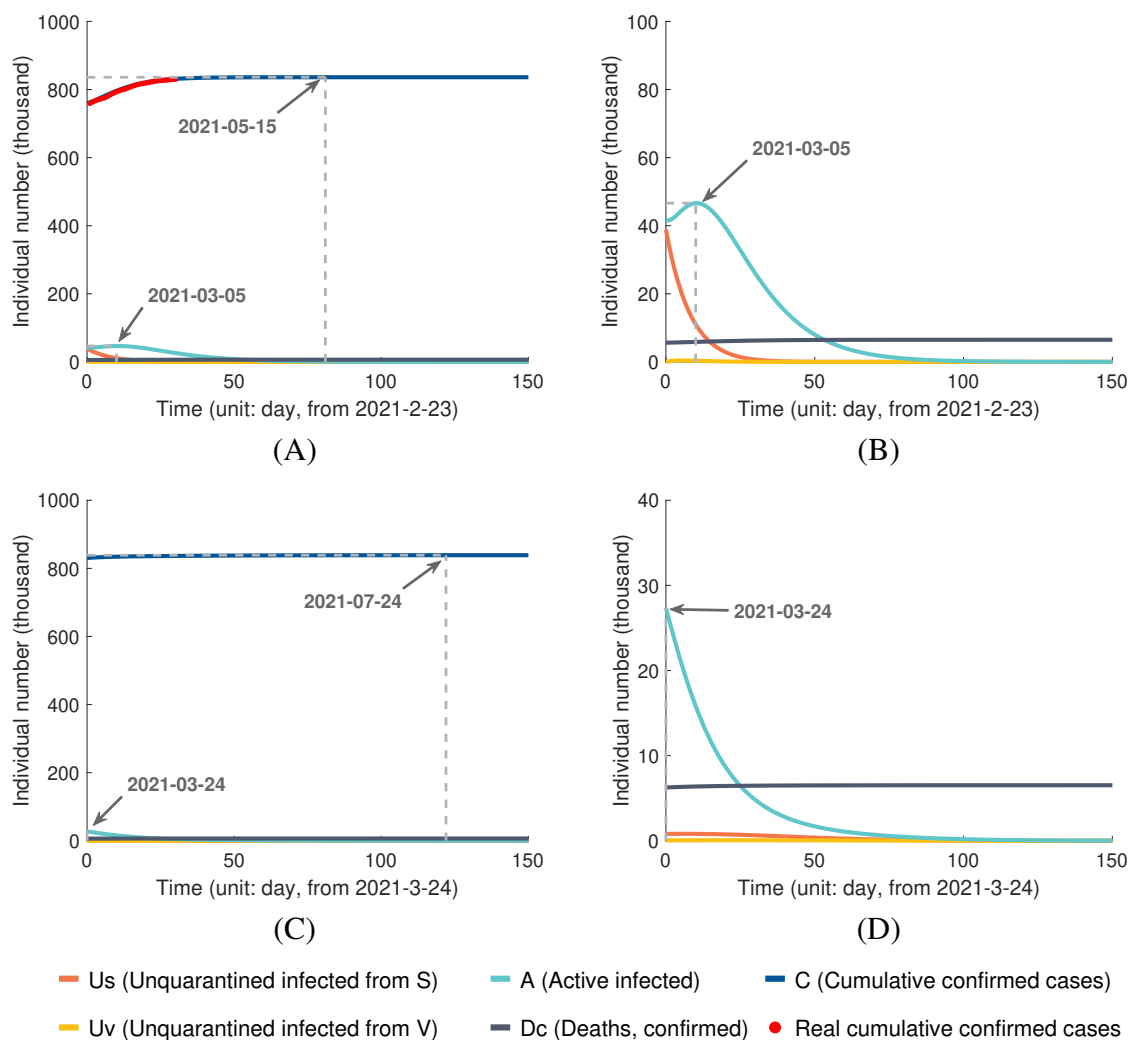


Figure 2: Inference and prediction of epidemic dynamics in Israel: (A) Parameter setting: vaccine efficacy $1 - \lambda_1 = 0.95$, daily vaccination rate $\eta/N = 0.605\%$ per day, duration of immunity $t_s = 8$ months, and with NPIs. (B) A zoom-in plot of (A) without C . (C) Parameter setting: all the parameters remain the same as (A) except that no NPIs after Mar 24 2021. (D) A zoom-in plot of (C) without C .

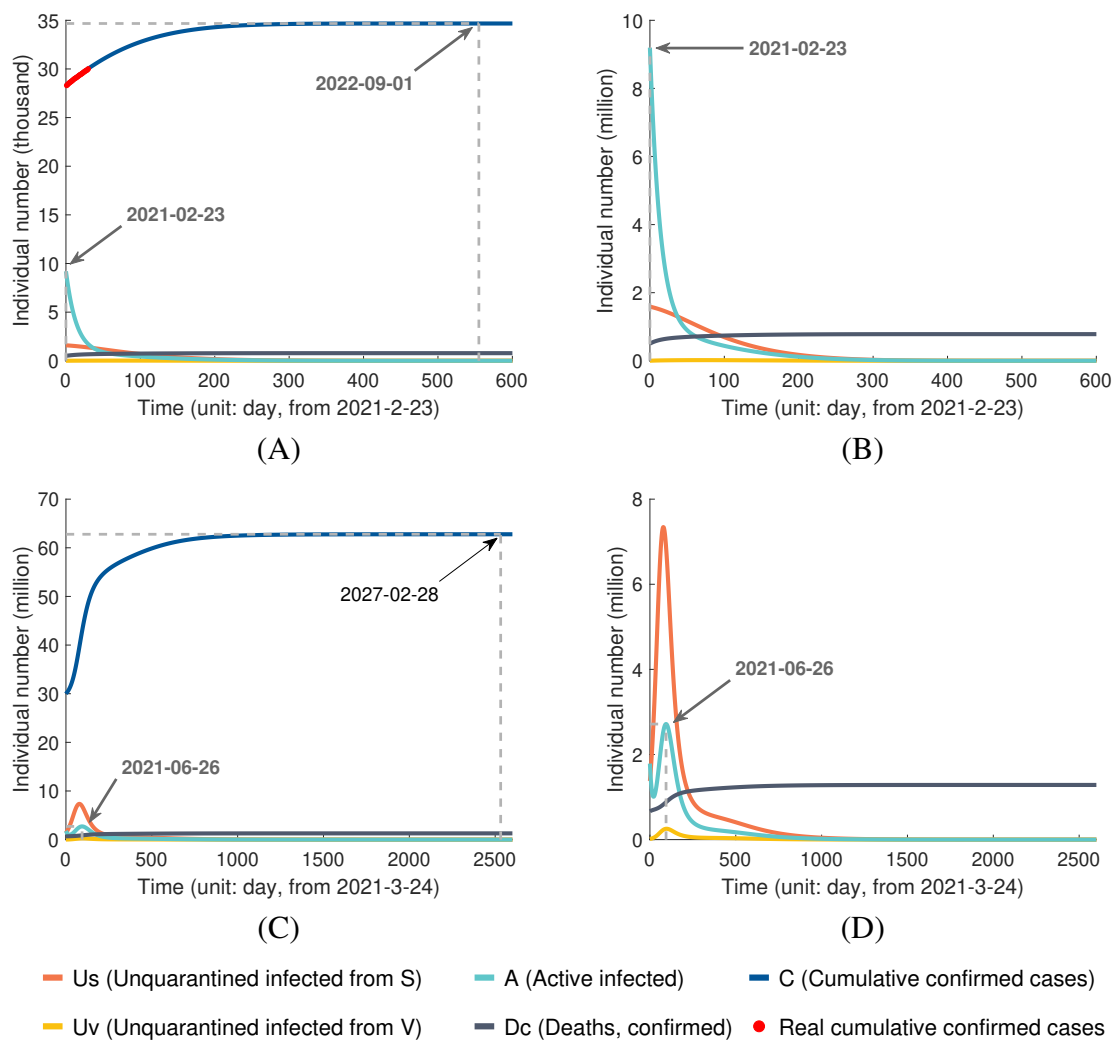


Figure 3: Prediction of epidemic dynamics in US with vaccination and multiple parameter settings: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$, daily vaccination rate $\eta/N = 0.268\%$, duration of immunity $t_s = 8$ months, and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

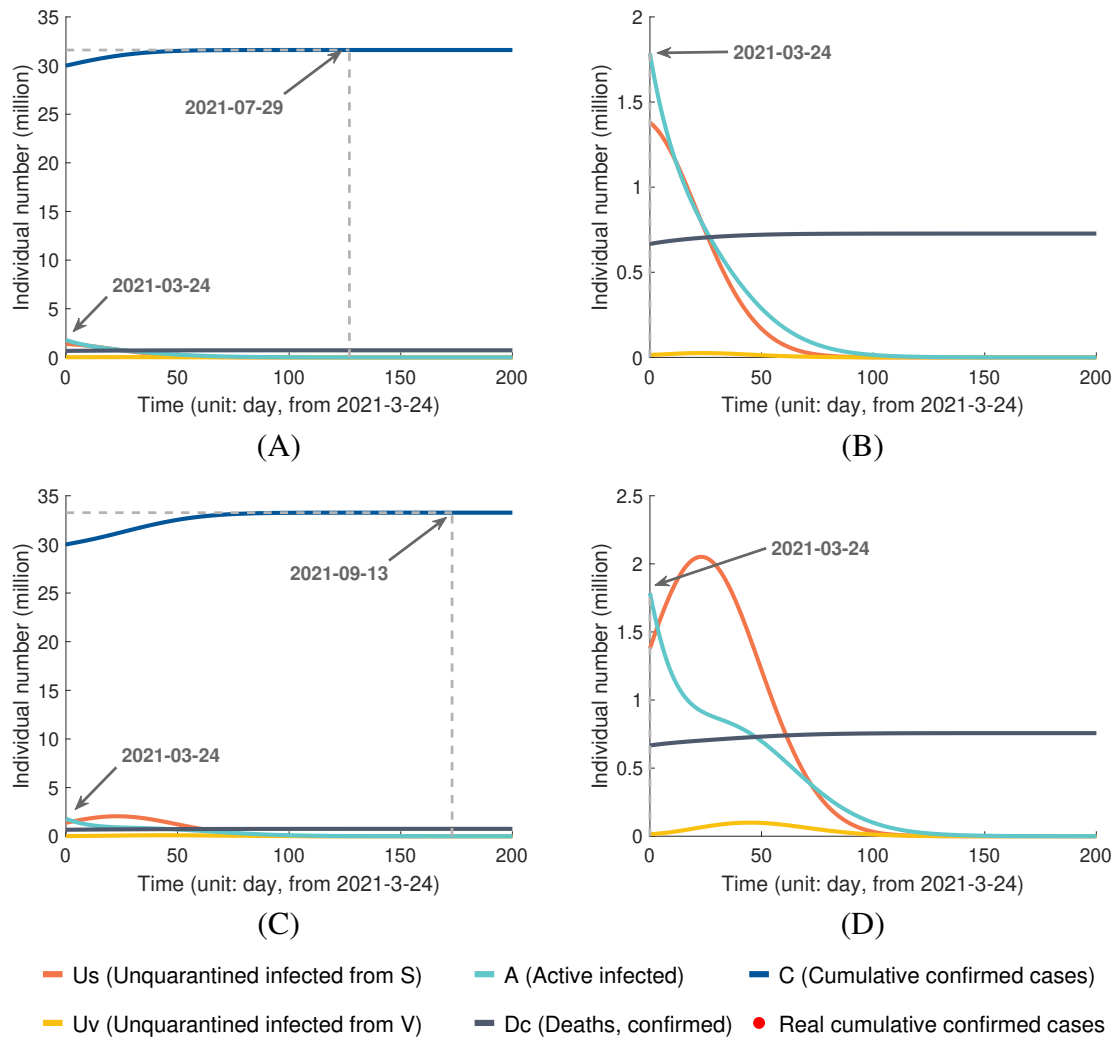


Figure 4: Prediction of epidemic dynamics in US with vaccination supposing a larger daily vaccination rate $\eta/N = 1\%$: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$, duration of immunity of 8 months, and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

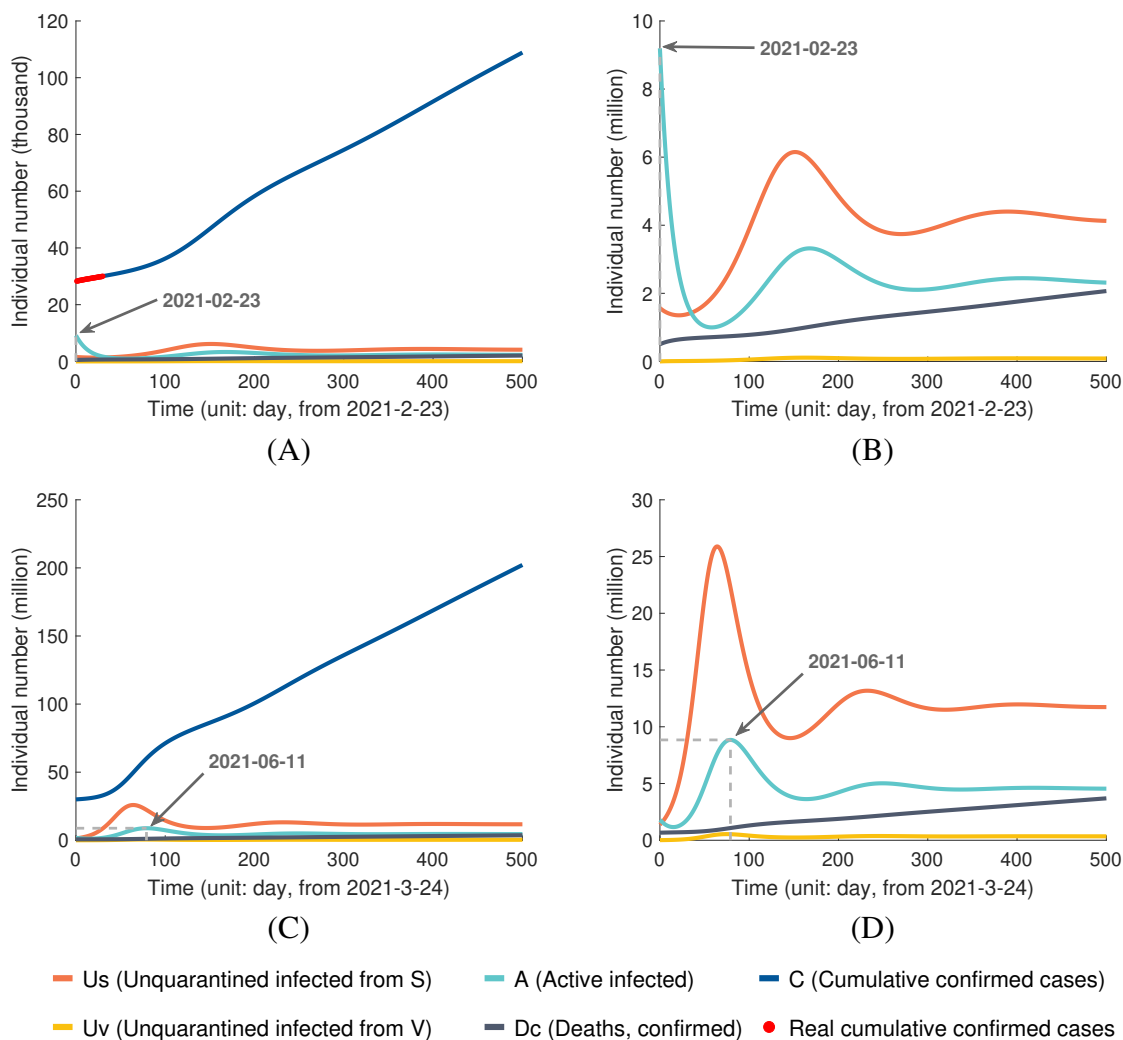


Figure 5: Prediction of epidemic dynamics in US under duration of immunization of three months: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$, daily vaccination rate $\eta/N = 0.268\%$, and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

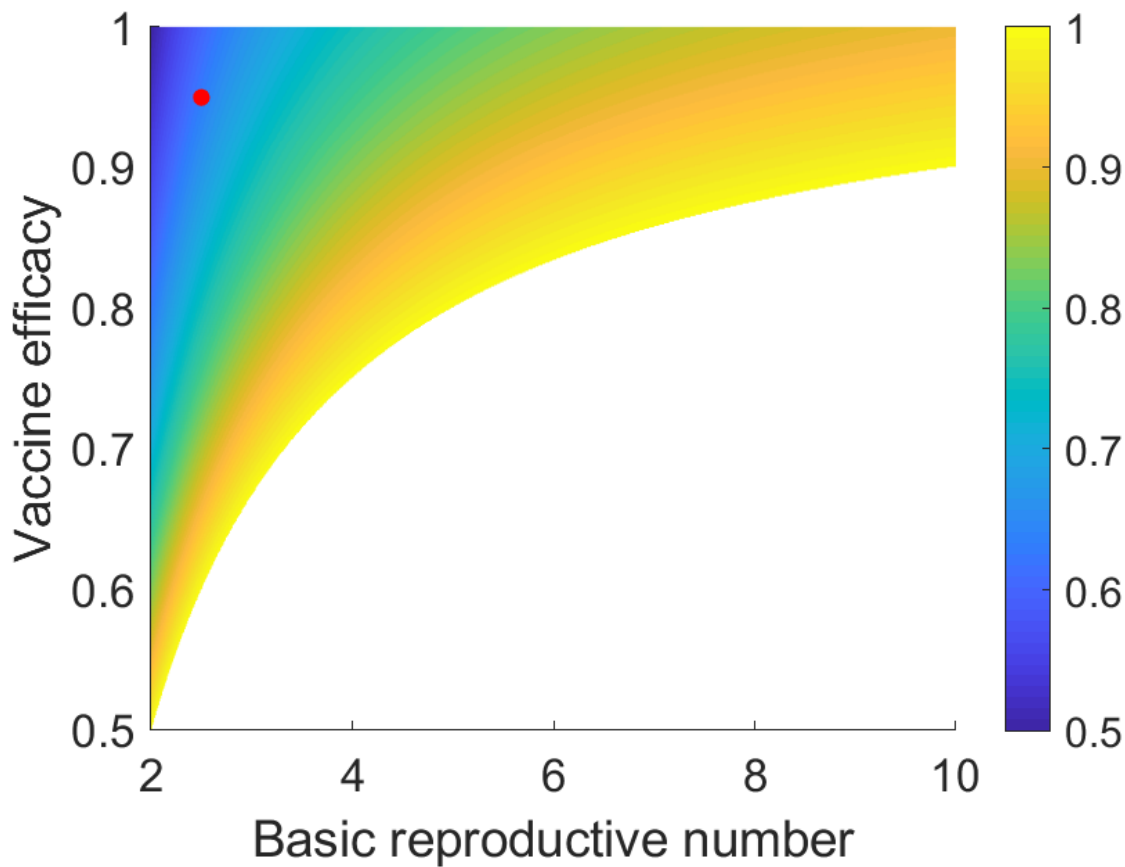


Figure 6: The minimum daily vaccination rate η/N required to effectively end the epidemic without NPIs for different values of basic reproductive number (R_0) and vaccine efficacy ($1 - \lambda_1$). Here we set $\lambda_2 = 1$. The color scheme indicates the daily vaccination rates in unit of $1/t_v$. Red dot: for $R_0 = 2.5$, $t_v = 100$ days and $1 - \lambda_1 = 0.95$, the minimum daily vaccination rate should be $\eta/N > 0.63\%$ per day.

Supplementary Materials
**Will the Large-scale Vaccination Succeed in Containing the
COVID-19 Epidemic and How Soon?**

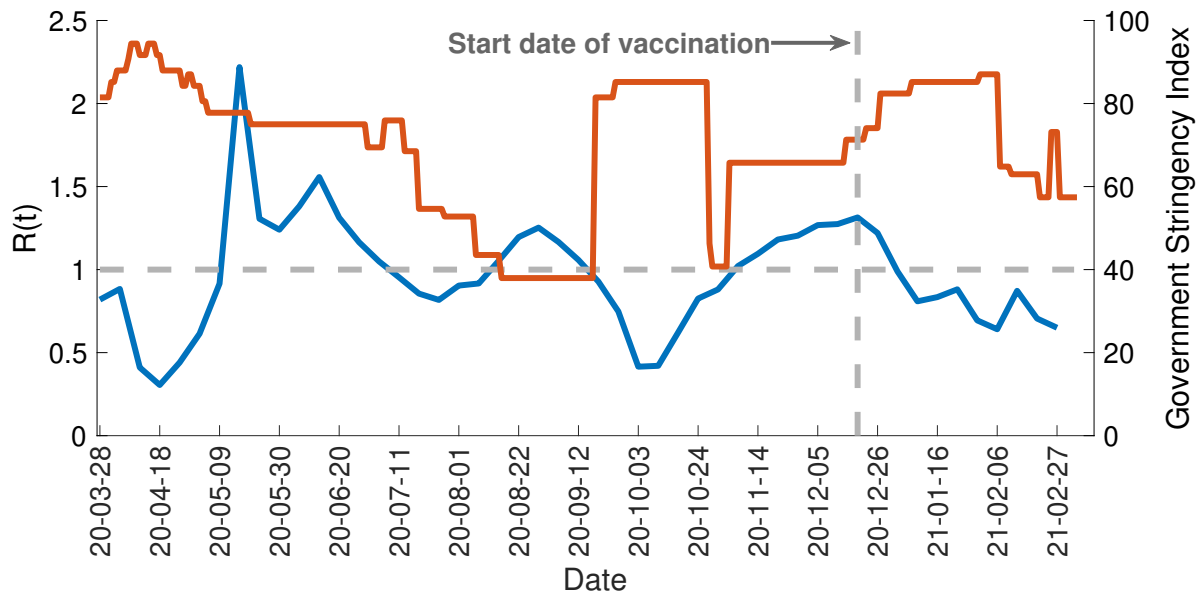


Figure S.1: Temporal dynamics of $R(t)$ and the Government Stringency Index in Israel. Blue line indicates $R(t)$ value estimated with the SUQC model. Red line is the Government Stringency Index adopted from OxCGRT.

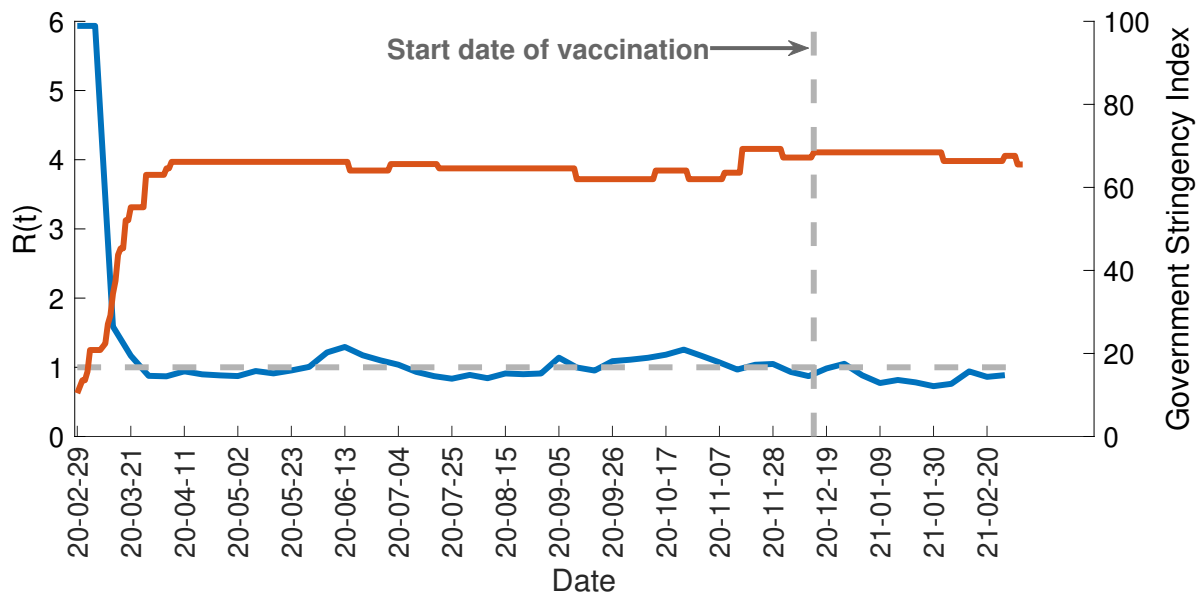


Figure S.2: Temporal dynamics of $R(t)$ and the Government Stringency Index in US. Blue line indicates $R(t)$ values estimated with the SUQC model. Red line is the Government Stringency Index adopted from OxCGRT.

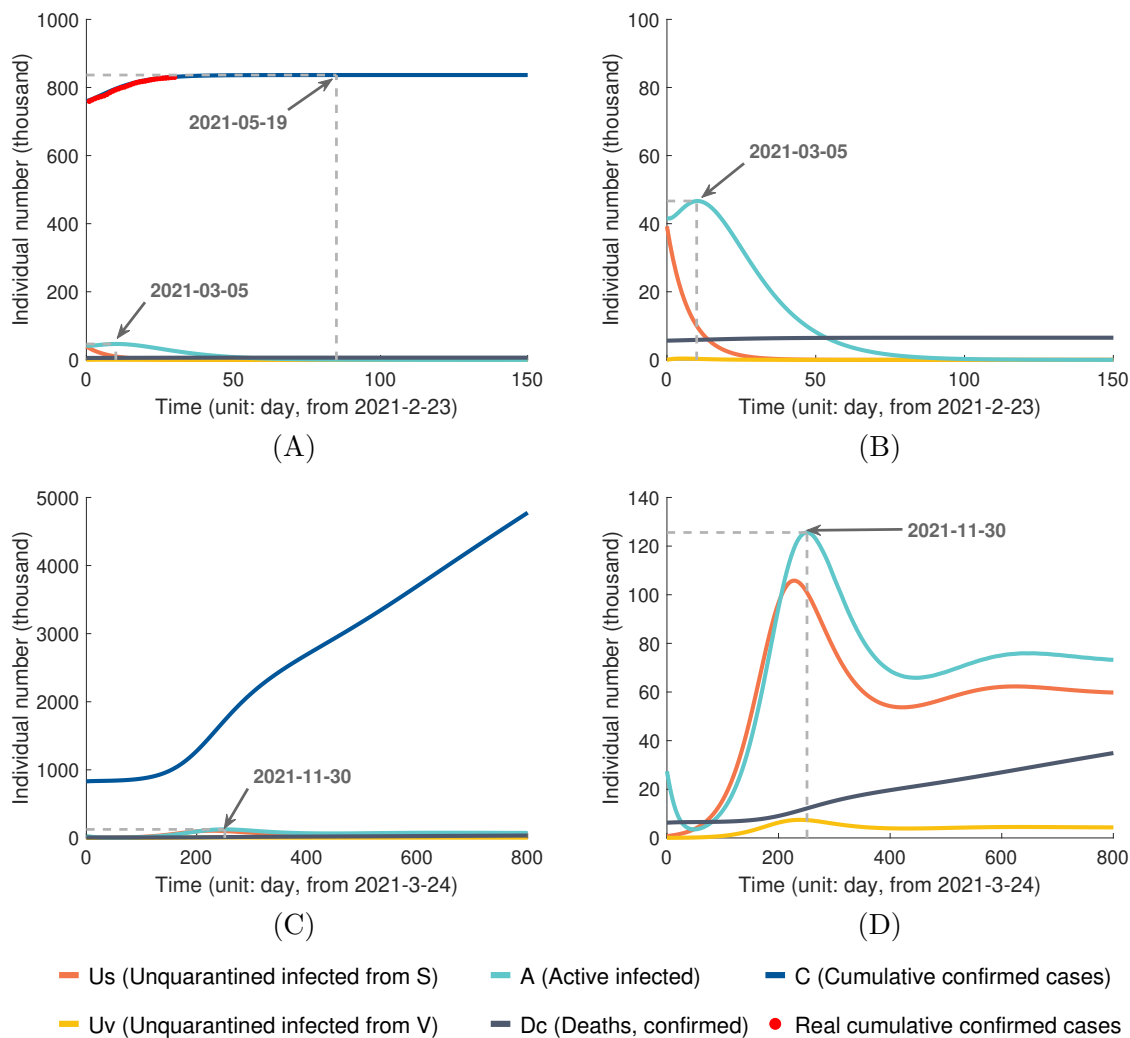


Figure S.3: Prediction of epidemic dynamics in Israel with the immunity duration of three months: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$, daily vaccination rate $\eta/N = 0.605\%$, and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

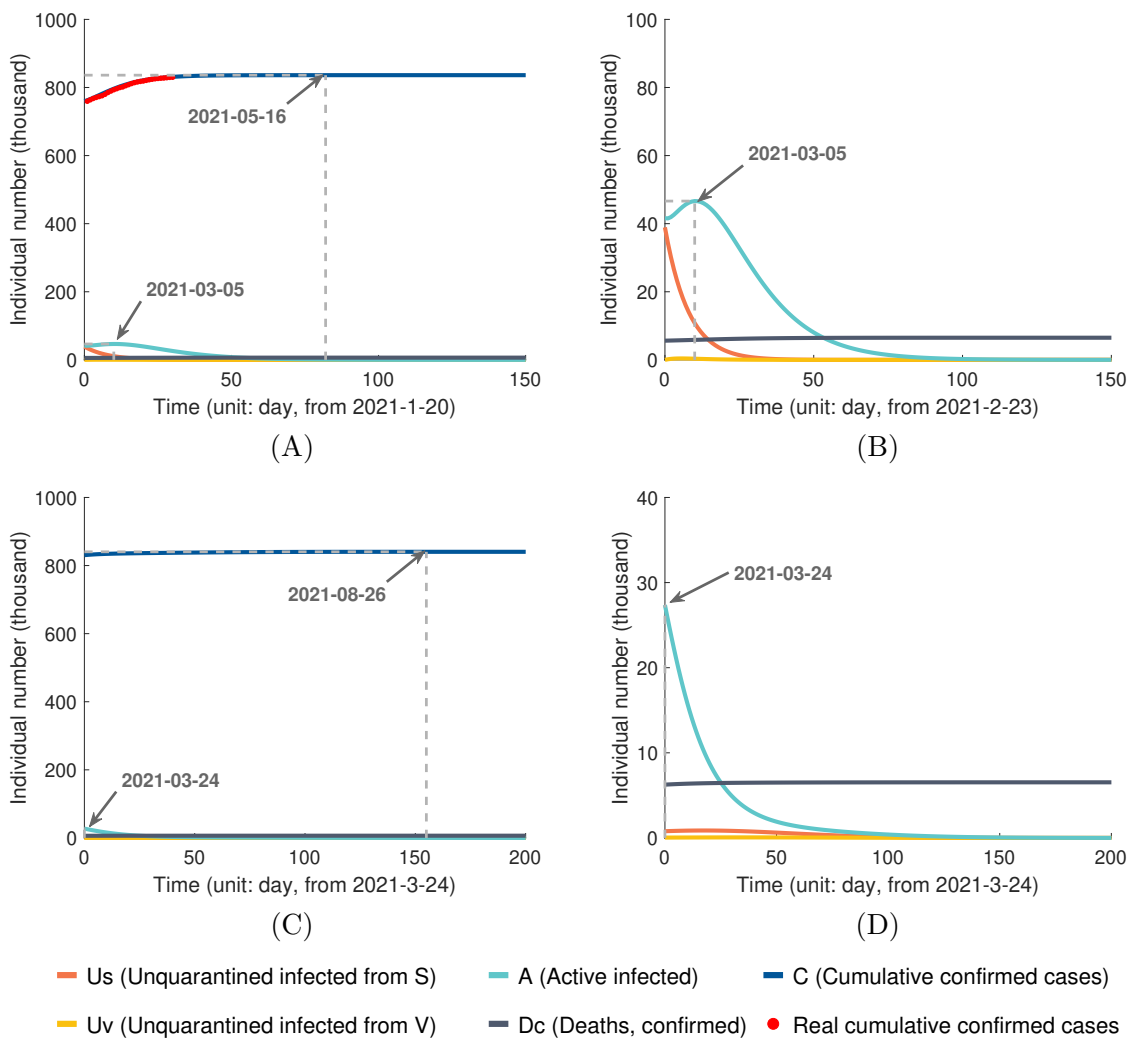


Figure S.4: Prediction of epidemic dynamics in Israel with the immunity duration of six months: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$, daily vaccination rate $\eta/N = 0.605\%$, and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

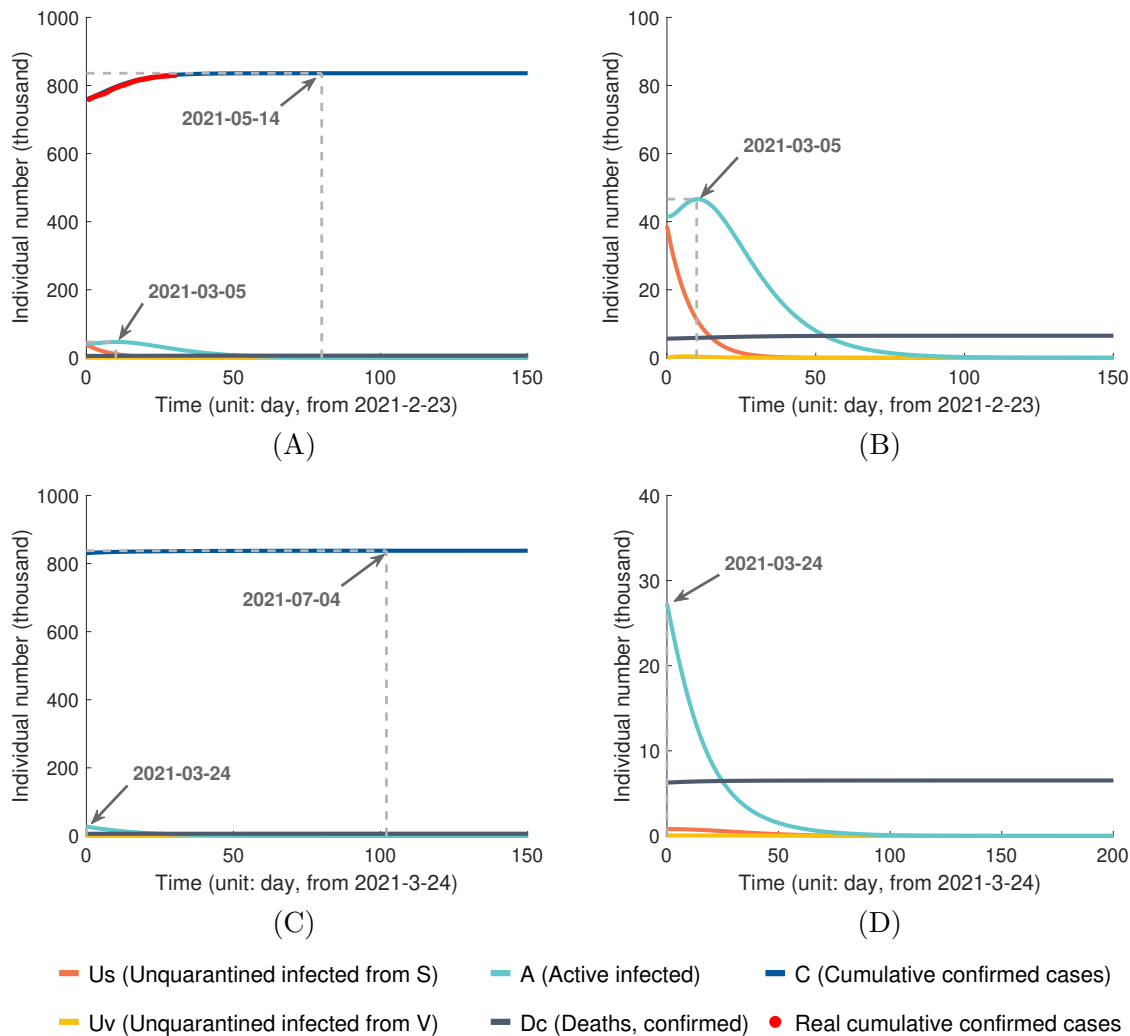


Figure S.5: Prediction of epidemic dynamics in Israel with the immunity duration 12 months: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$, daily vaccination rate $\eta/N = 0.605\%$, and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

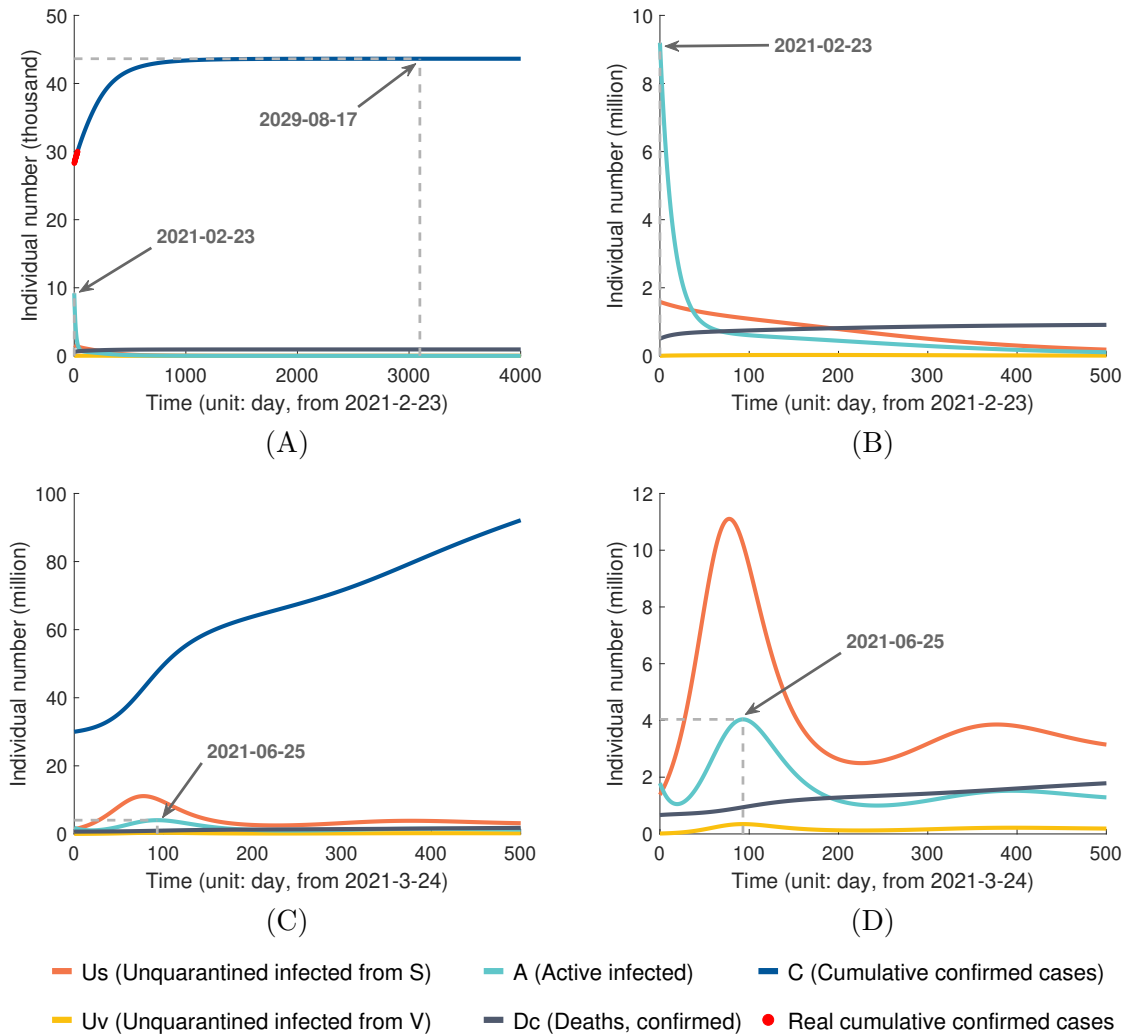


Figure S.6: Prediction of epidemic dynamics in USA with the immunity duration of six months: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$, daily vaccination rate $\eta/N = 0.268\%$, and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

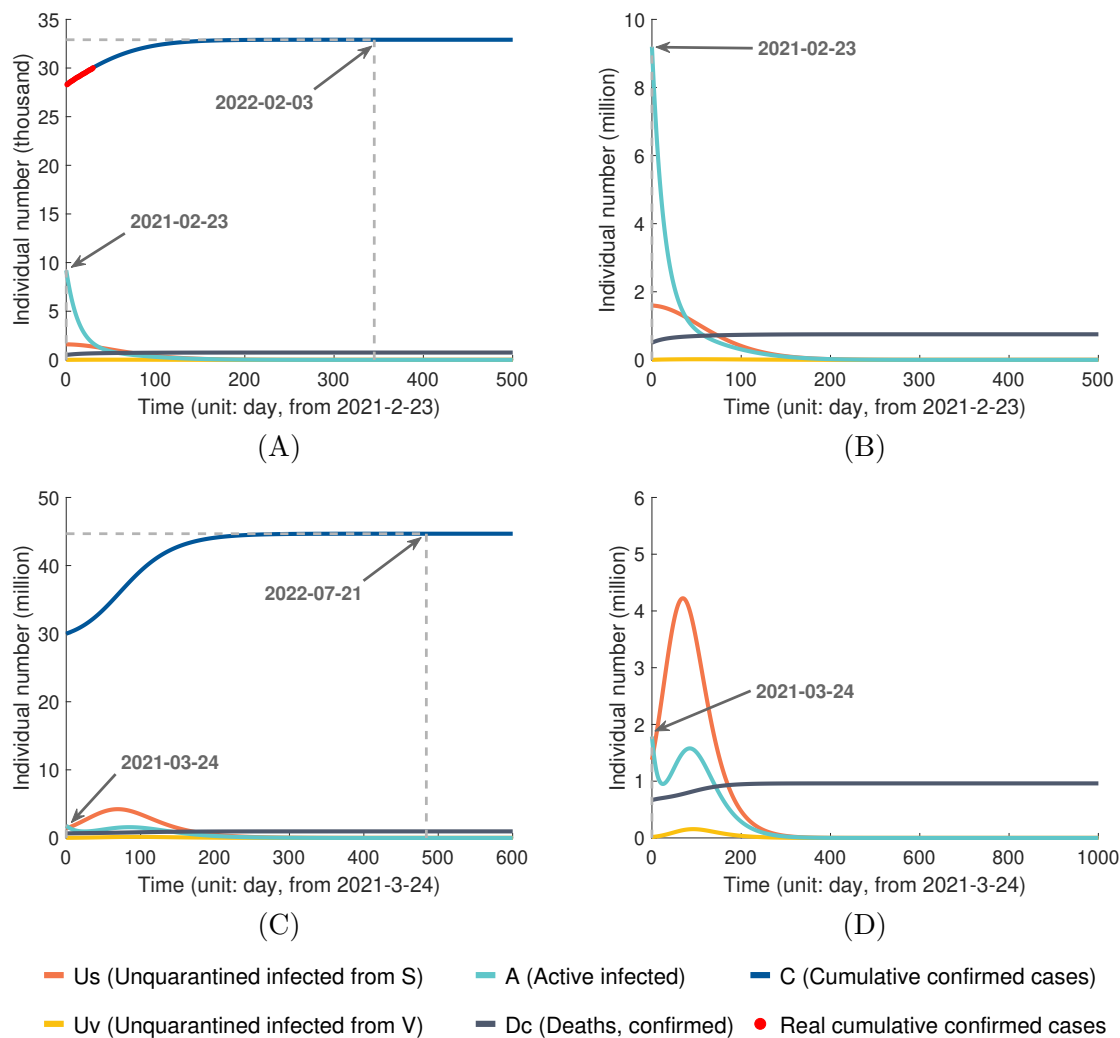


Figure S.7: Prediction of epidemic dynamics in USA with the immunity duration of 12 months: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$, daily vaccination rate $\eta/N = 0.268\%$, and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

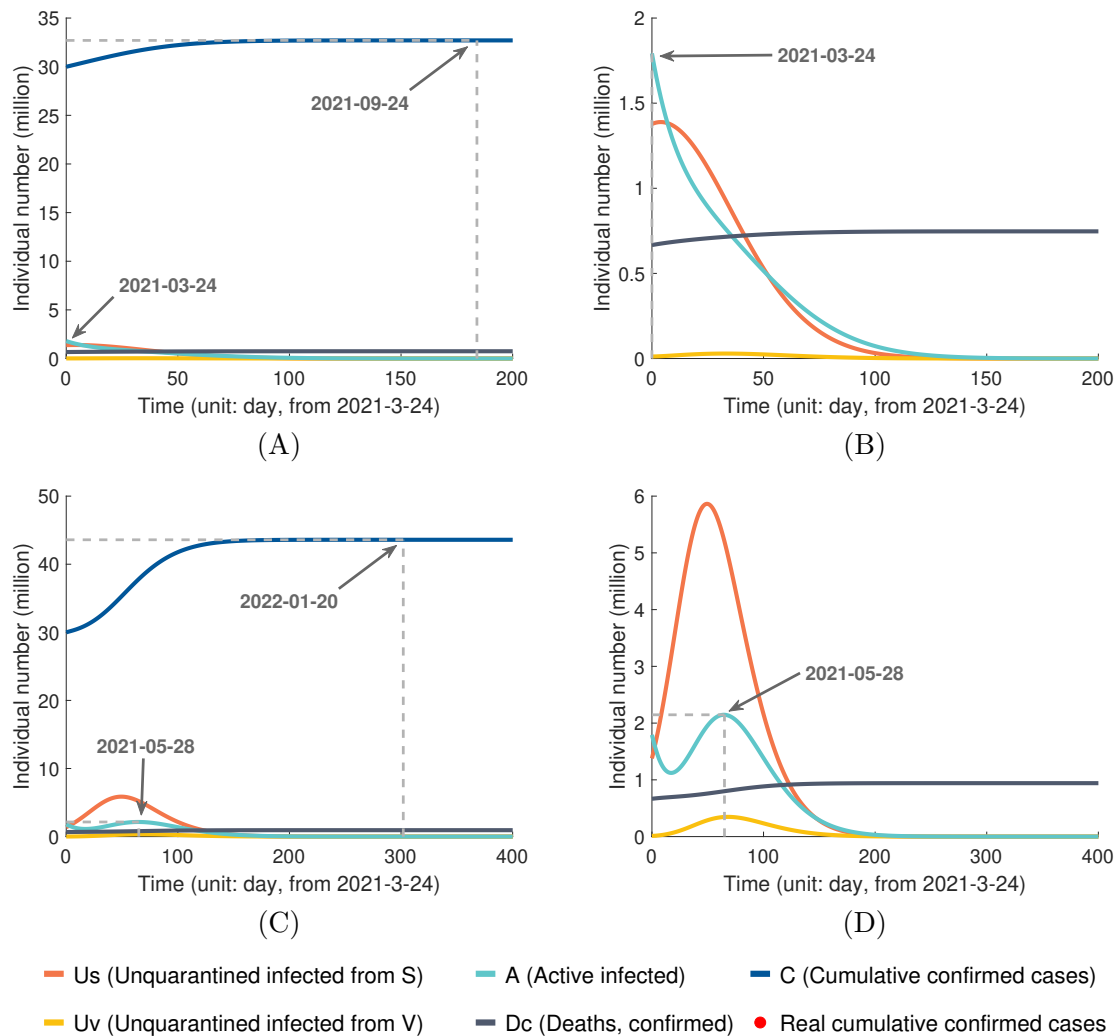


Figure S.8: Prediction of epidemic dynamics in USA with the immunity duration of three months and daily vaccination rate $\eta = 0.01N$: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$ and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

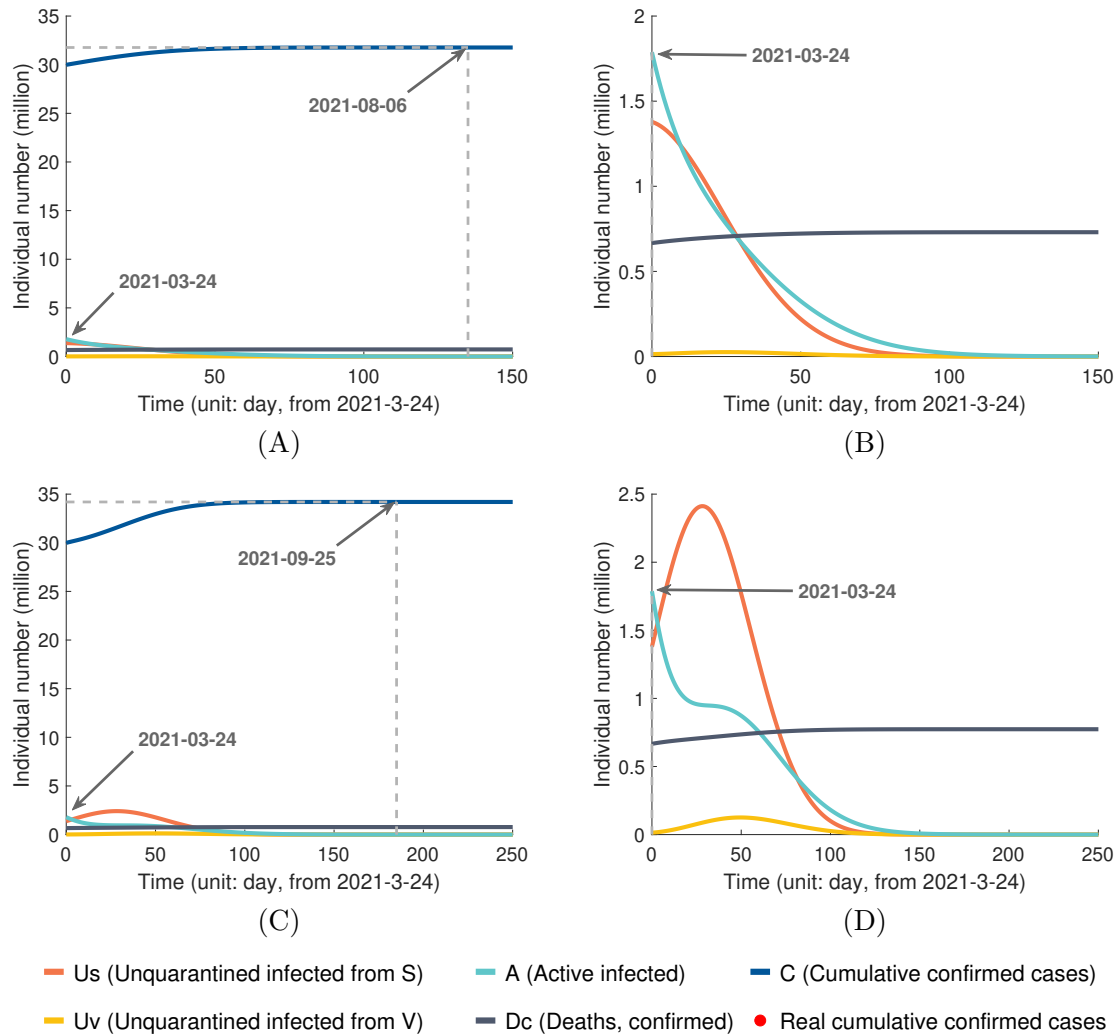


Figure S.9: Prediction of epidemic dynamics in USA under duration of immunization of six months and daily vaccination rate $\eta = 0.01N$: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$ and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.

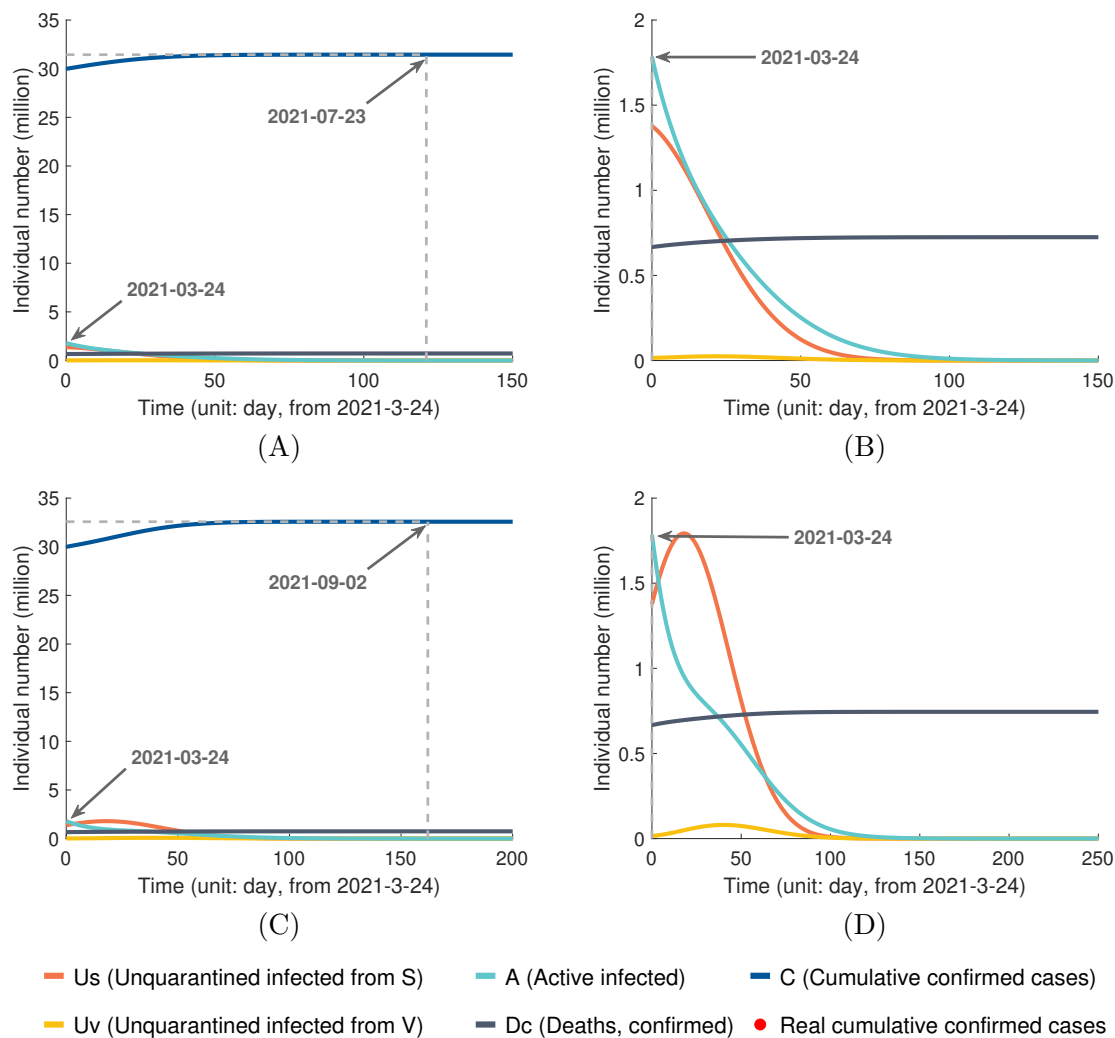


Figure S.10: Prediction of epidemic dynamics in US under duration of immunization of 12 months and daily vaccination rate $\eta = 0.01N$: (A) and (B) Vaccine efficacy $1 - \lambda_1 = 0.95$ and with NPIs. (C) and (D). All the other parameters are identical to (A) and (B), and with no NPIs.