WHO vaccination protocol can be improved to save more lives – Supplementary information

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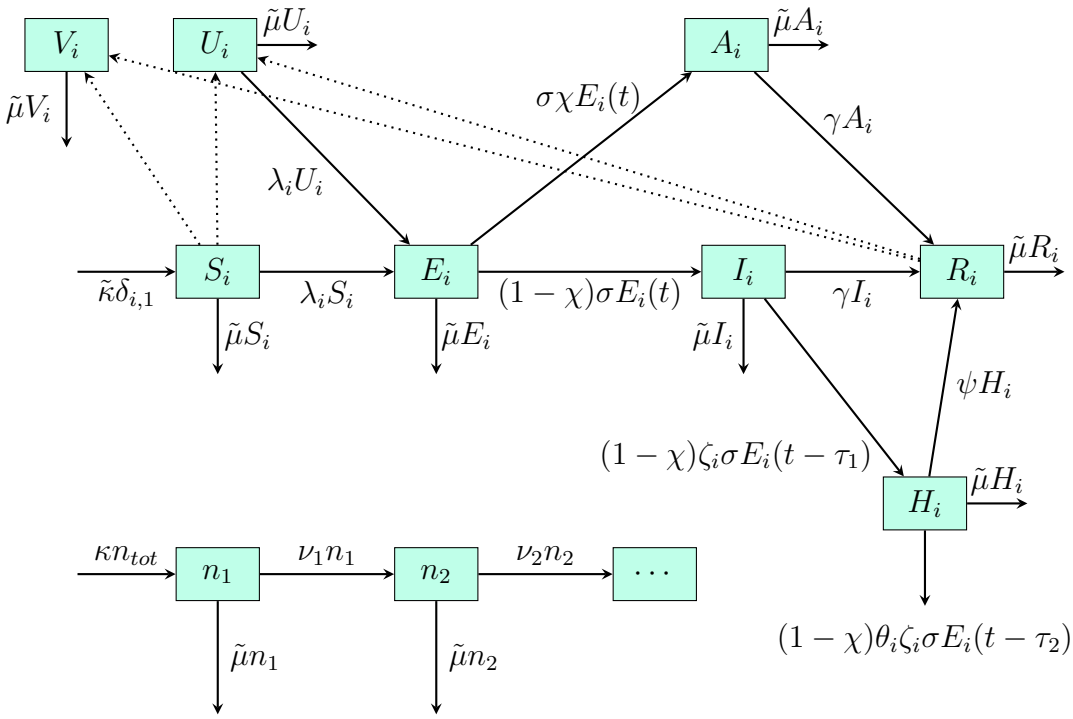
1 Supplementary Methods

Epidemiological model

We consider an age-stratified model with homogeneous mixing (mean-field description). The following age groups considered: 0 to 9, 10 to 19, 20 to 29, 30 to 39, 40 to 49, 50 to 59, 60 to 69, 70 to 79 and 80 or more years of age. The population in each age group is divided into different compartments described in Table 3. All variables are proportions with respect to the initial population N_0 (the present population changes due to mortality and birth). The parameters required by the model are given in Tables 3, 3 and 3. A schematic representation of the model is given in Figure 1.



Supplementary Figure 1: Schematic representation of the epidemiological model in Eq. (1). The continuous arrows represent rates between variables. The dotted lines indicate the proportion with respect to N_0 of vaccine shots (see below). In the diagram $\tilde{\mu} = \mu N/N_0$ and $\tilde{\kappa} = \kappa N/N_0$, with μ and κ the death and birth rates in the population, respectively, and N the current total population. The proportion in the age group i with respect to N_0 is denoted by n_i and the aging rate ν_i from group i is given by the inverse of the time span of the age group in the time unit used.

The delayed system of ordinary differential equations corresponding to Figure 1 are then

$$
\begin{aligned}
&\frac{dS_i}{dt} = -\lambda_i S_i - \tilde{\mu} S_i + \tilde{\kappa}\delta_{i,1} - \rho_i^{(S)}(t), \quad \frac{dE_i}{dt} = \lambda_i S_i - \sigma E_i - \tilde{\mu} E_i,\\
&\frac{dI_i}{dt} = (1-\chi)\sigma E_i - \gamma I_i - (1-\chi)\zeta_i \sigma E_i(t-\tau_1) - \tilde{\mu} I_i,\\
&\frac{dA_i}{dt} = \chi\sigma E_i - \gamma A_i - \tilde{\mu} A_i,\\
&\frac{dH_i}{dt} = -\psi H_i + (1-\chi)\zeta_i\sigma E_i(t-\tau_1) - \theta_i\zeta_i\lambda_i E_i(t-\tau_2) - \tilde{\mu} H_i,\\
&\frac{dR_i}{dt} = \gamma I_i + \gamma A_i + \psi H_i - \tilde{\mu} R_i - e_v \rho_i^{(R)}(t),\\
&\frac{dV_i}{dt} = e_v \rho_i(t) - \tilde{\mu} V_i, \quad \frac{dU_i}{dt} = (1-e_v)\rho_i(t) - \tilde{\mu} U_i,\\
&\rho_i(t) = \rho_i^{(S)}(t) + \rho_i^{(R)}(t),
\end{aligned}
\tag{1}
$$

where all variables are taken at time t except when otherwise explicited, $\rho_i^{(S)}(t)$ and $\rho_i^{(R)}(t)$

are the number of vaccines (comprising the required number of doses for immunization) divided by N_0, at time t, given to the susceptible and recovered individuals, respectively, and e_v the efficacy of the vaccine. For economy of space and notation we kept the aging rates between age groups implicit. The force of infection in Eq. (1) for the i-the age group is given by

$$\lambda_i = \sum_{j=1}^{M} \beta_{i,j}(I_j + \xi A_j)/n_i, \tag{2}$$

where $\beta_{i,j}$ are the component of the transmission matrix giving the probability per unit of time that a symptomatic infected individual (I_j) of age group j to infect a susceptible individual (S_i) of age group i. For an asymptomatic individual (A_j) this probability is $\chi\beta_{i,j}$. It is worth to show how this expression is obtained: We start by noting that $\lambda_i S_i N \delta t$ gives the total number of susceptible individuals infected during the (small) time interval δt. The contact matrix with elements $C_{i,j}$ is defined as the average number of contacts per unit of time of an individual of age group j with any individual of age group i. The proportion of such contacts with susceptible individuals is $S_i N_0/N_i$ (N_i being the population of age group i). The total number of contacts between all infected (I_j) individuals of any age group with susceptible individuals of age group i during the time interval δt is given by $\sum_j (S_i N_0/N_i) C_{i,j} I_j \delta t$. Now denoting the probability of transmission per contact by p_c and supposing it is independent of which age groups are interacting, we obtain that

$$\lambda_i S_i \, N_0 \delta t = \sum_{j=1}^{M} p_c S_i \frac{N_0}{N_i} C_{i,j} I_j N_0 \delta t. \tag{3}$$

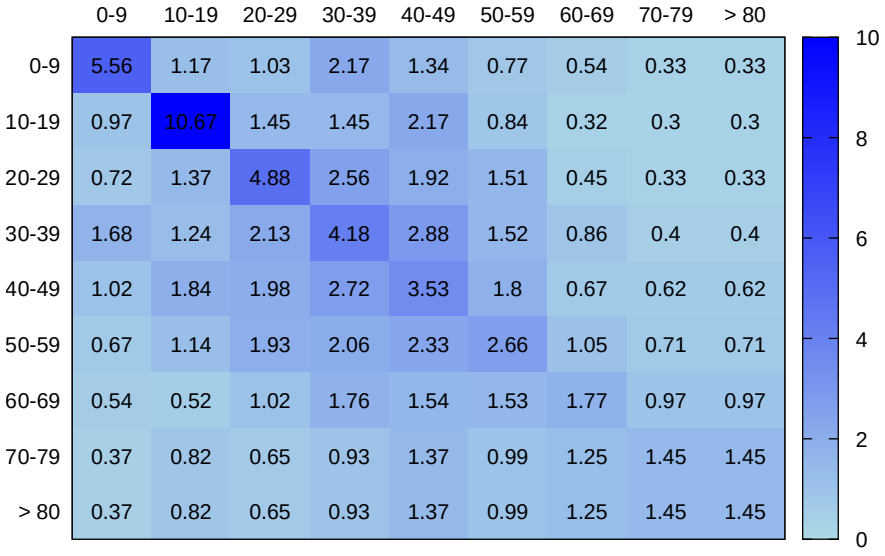
To add the contribution o asymptomatic individuals we replace I_j by $I_j + \xi A_j$ in this last equation, and then obtain the expression in Eq. (2) by identifying $\beta_{i,j} = p_c C_{i,j}$.

The numeric solution for the model equation in Eq. (1) is implemented in the low level C language using a Runge-Kutta fourth order integrator. All scripts and programs are written in the Maple computer algebra package [40]. Since the present model is essentially a mean-field simplification of the more complex phenomenology of an epidemic spread, and due to the time-delay in the equations, we avoid negative variable values by properly testing for positivity at each time step. Otherwise, the system equations have all the required consistency properties.

The contact matrix varies with time due to social distancing and behavioral changes during the pandemic. We suppose here that such time variation can be represented by a single time-dependent constant factor $\omega(t)$ such that $C_{i,j}(t) = \omega(t) C_{i,j}(0)$, with $C_{i,j}(0)$ the components of the contact matrix prior to the pandemic. By defining $P(t) \equiv \omega(t) p_c$ we have $\beta_{i,j} = P(t) C_{i,j}(0)$.

Contact matrix

The contact matrix, with components $C_{i,j}$, is obtained as described in the main text based on Reference [35], is shown as a heat map in Figure 2.



Supplementary Figure 2: Heat map for the estimate of the contact matrix. The entries give the number of contacts per day.

Implementing the superspreaders group

Alongside the nine age groups defined above, we introduce a tenth group composed by 20% of the population in the age group of 30 to 39 years old (the fourth age group), with the same epidemiological parameters but different number of contacts per unit of time, such that the new contact matrix $\overline{C}$ is

$$\begin{aligned}
&\overline{C}_{i,j} = C_{i,j}, \quad i = 1, \ldots, M, \;\; i \neq 4 \;\; j = 1, \ldots, M, \\
&\overline{C}_{4,j} = 0.8\, C_{4,j}, \quad j = 1, \ldots, M, \\
&\overline{C}_{i,M+1} = \alpha C_{i,4}, \quad \overline{C}_{i,M+1} = \alpha C_{i,4}, \quad i = 1, \ldots, M, \quad \overline{C}_{M+1,M+1} = \alpha C_{4,4},
\end{aligned} \tag{4}$$

where α is a contact factor denoting the excess in contacts with respect to the average of the $30-39$ years age group. Supposing social distancing α is kept at the value $\alpha = 1$ and at a later stage, mimicking a return to normal activities, it is set to a value $3 \leq \alpha \leq 10$ (see

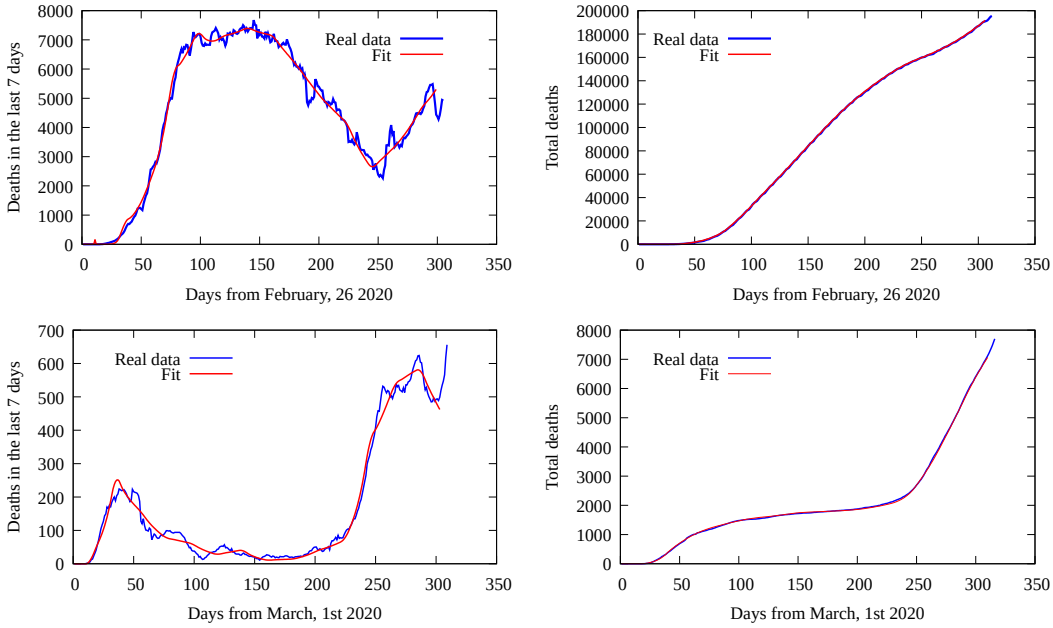
main article).

Fitting $P(t)$ from data

The constant values of the step function for $P(t)$ at each interval are obtained by numerically minimizing the quadratic error:

$$\mathcal{E} = \sum_{n=1}^{N_{days}} \left(\Delta_a(n) - \Delta_{mod}(n)\right)^2, \tag{5}$$

where $\Delta_a(i)$ and $\Delta_{mod}(i)$ are the actual and fitted number of deaths over the last 7 days at day n, respectively, and N_{days} is the total number of days considered for the fitting. Figure 3 shows the real and fitted data for Portugal and Brazil, evidencing the good quality of the fit.

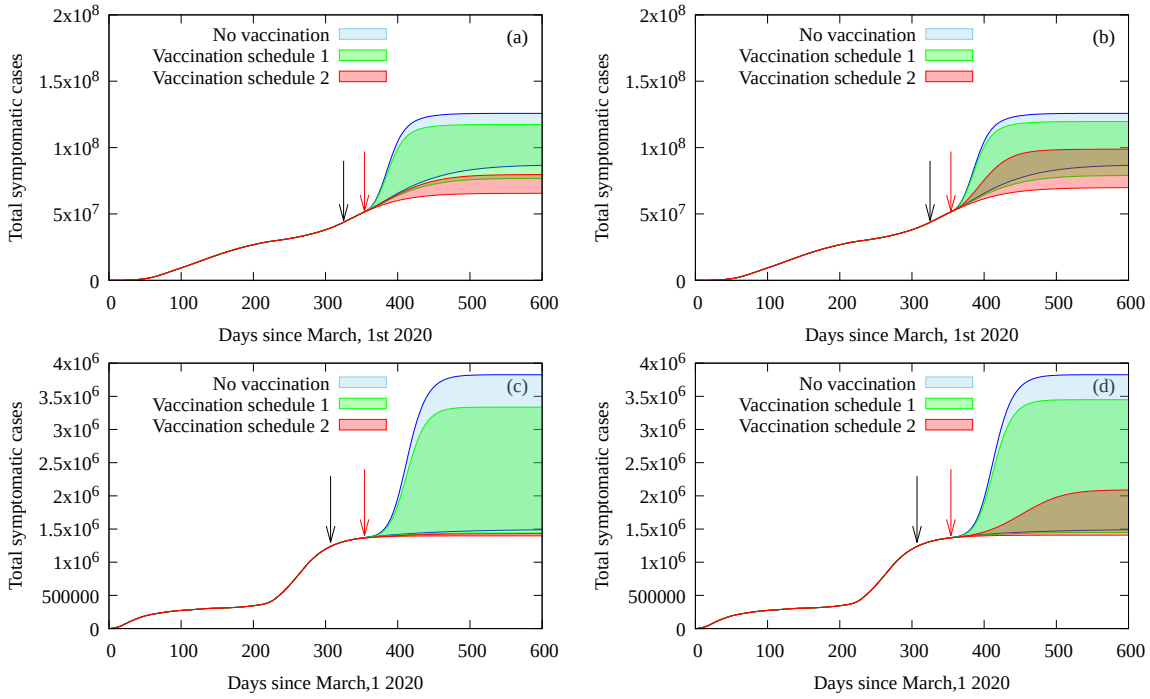


Supplementary Figure 3: Actual and fitted number of deaths on the last 7 days and total deaths by COVID-19 for Brazil (top) and Portugal (bottom).

2 Supplementary discussion

The total number of symptomatic cases for the vaccination (and without any vaccination) scenarios described in the main text are shown in Fig. 4. Similarly to the number of deaths, including the superspreaders (in the sense discussed in the main text) in the first group to be vaccinated results in a significant reduction in the number of COVID-19 cases, which at its turn results in reduction in hospitalizations. We note that this reduction in the total

number of symptomatic cases also reduces the number of individuals with long-term health effects due to COVID-19, also resulting in a reduction in health spending in each country.



Supplementary Figure 4: Total number of symptomatic cases: Brazil (a) $e_v = 0.95$, (b) $e_v = 0.7$, and Portugal (c) $e_v = 0.95$ and (d) $e_v = 0.7$, for the vaccinations campaigns with superspreaders as described in the main text. The black arrows indicate starting of vaccination and red arrows the moment superspreaders return to full social contact ($3 \leq \alpha \leq 10$). The lower and upper curves defining the green and red shaded areas correspond to $\alpha = 3$ and $\alpha = 10$, respectively.

3 Supplementary tables

Variable	Description
S_i	Proportion of susceptible individuals
E_i	Proportion of exposed individual in the incubation period and not contagious.
I_i	Proportion of infected symptomatic individuals (contagious).
A_i	Proportion of infected asymptomatic individuals (contagious).
H_i	Proportion of hospitalized individuals.
R_i	Proportion of recovered individuals.
V_i	Proportion of vaccinated individuals without primary vaccination failure.
U_i	Proportion of vaccinated individuals with primary vaccination failure.
n_i	Proportion of the population in the i-th age group.

Supplementary Table 1: Variables in the epidemiological model. All proportions are with respect to the initial population N_0. The index $i = 1, \ldots, M$ denotes the age group ($M = 9$ in the present case).

Variable	**Definition**	Valor (IC 95%) [Ref]
ψ	Recovery rate from hospitalation	1/17.5 days^{-1} [18,32]
σ	Inverse of incubation time	1/5.0 days^{-1} [31]
γ	Recovery rate for non hospitalized individuals	1/3.69 days^{-1} [34]
θ_i	Fatality rate among hospitalized individuals	$L_i^{(0)}/\zeta_i$
τ_1	Median time from first symptoms to hospitalization	3.3 [31]
τ_2	Average time from first symptoms to death	16.8 [18]
χ	Proportion of asymptomatic cases	17.9% [33]
ξ	Contagiousness of asymptomatic individuals with respect to asymptomatic individuals	55% [34]

Supplementary Table 2: Parameters in the epidemiological model. The index i refers to the age group. If there is no such index the parameter has the same value for all groups. $L_i^{(0)}$ and ζ_i are given in Tables 3 and 3.

0 – 9	10 – 19	20 – 29	30 – 39	40 – 49	50 – 59	60 – 69	70 – 79	≥80
0.0%	0.2%	0.2%	0.2%	0.4%	1.3%	3.6%	8.0%	14.8

Supplementary Table 3: Infection fatality ratio $L_i^{(0)}$ according to age group [18].

0 a 9	10 a 19	20 a 29	30 a 39	40 a 49	50 a 59	60 a 69	70 a 79	80 or more
0%	0.408%	1.04%	3.43%	4.35%	8.16%	11.8%	16.6%	18.4

Supplementary Table 4: Hospitalization probability ζ_i for each age group [18].

Reference

[40] Bernardin L., Chin P., DeMarco P., et al. *Maple Programming Guide*. Maplesoft, a division of Waterloo Maple Inc. (Toronto, 2013).