Supplementary Information - Report 33: Modelling the allocation and impact of a COVID-19 vaccine

Alexandra B Hogan^[1], Peter Winskill^[1], Oliver J Watson[1], Patrick GT Walker[1], Charles Whittaker[1], Marc Baguelin[1], David Haw[1], Alessandra Løchen[1], Katy A M Gaythorpe[1], Imperial College COVID-19 Response Team[1], Farzana Muhib[2], Peter Smith[3], Katharina Hauck[1], Neil M Ferguson[1], Azra C Ghani[1]

1. MRC Centre for Global Infectious Disease Analysis & WHO Collaborating Centre for Infectious Disease Modelling, Abdul Latif Jameel Institute for Disease and Emergency Analytics (J-IDEA), Imperial College London
2. PATH, Seattle, USA
3. Business School, Imperial College London

^Contributed equally

Correspondence a.hogan@imperial.ac.uk; p.winskill@imperial.ac.uk; a.ghani@imperial.ac.uk

SUGGESTED CITATION
AB Hogan, P Winskill, OJ Watson *et al*. Modelling the allocation and impact of a COVID-19 vaccine. Imperial College London (25-09-2020), doi: https://doi.org/10.25561/82822.

1. Additional Figures

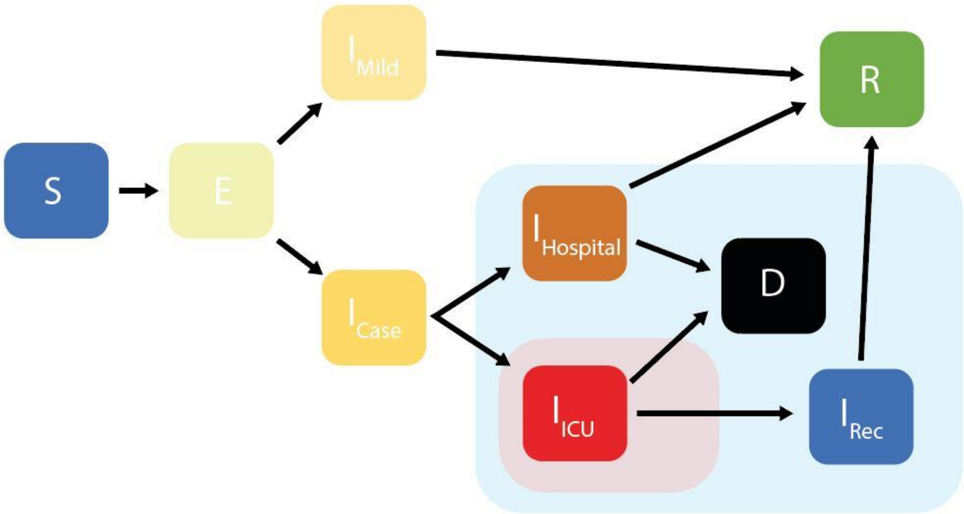

Figure S1: Simplified Schematic of the SARS-CoV-2 Transmission Model (reproduced from [1]). The flows are shown for the unvaccinated group. Individuals in the susceptible (S), exposed (E) and recovered (R) compartments can be vaccinated.

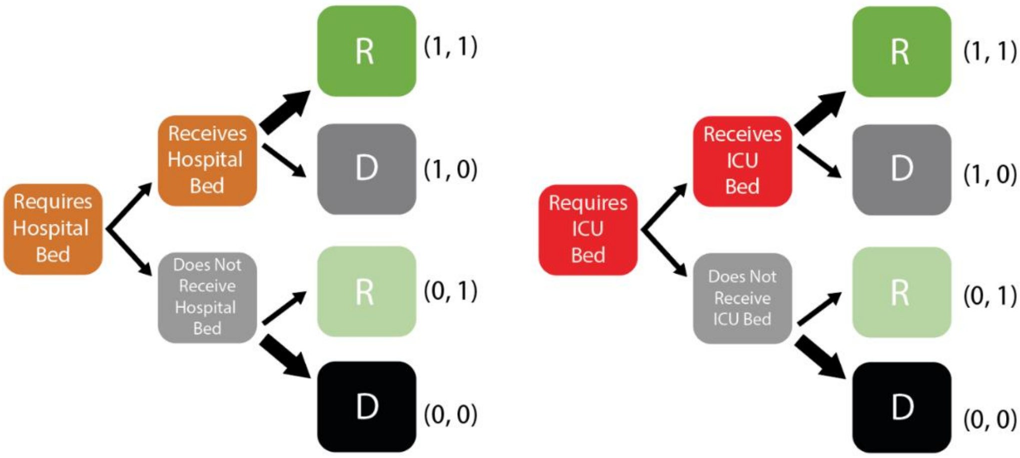

Figure S2: Pathways for Receiving Healthcare for Those That Require Hospital Care (reproduced from [1]). Those receiving a bed are subject to a lower probability of mortality than those who do not. Notation to the right-hand side of each box describes the compartment in terms of the notation introduced in the mathematical details below.

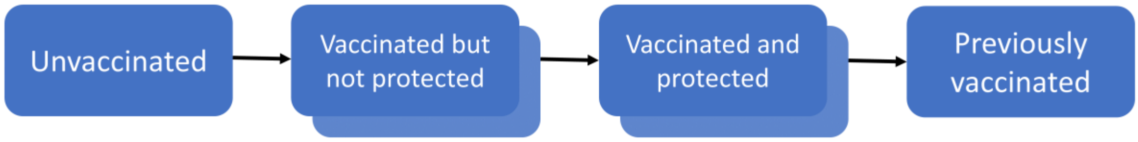

Figure S3: Simplified Schematic of Vaccination in the Transmission Model. Vaccination status is stratified into 6 categories - those that are unvaccinated (v0), those that have recently been vaccinated but are not yet protected (v1 and v2) and those that are vaccinated and protected (v3 and v4) and those that have previously been vaccinated but are no longer protected (v5). Protection may refer to partial protection. Previously vaccinated individuals are not modelled being revaccinated, due to all vaccination occurring within a one-month period.

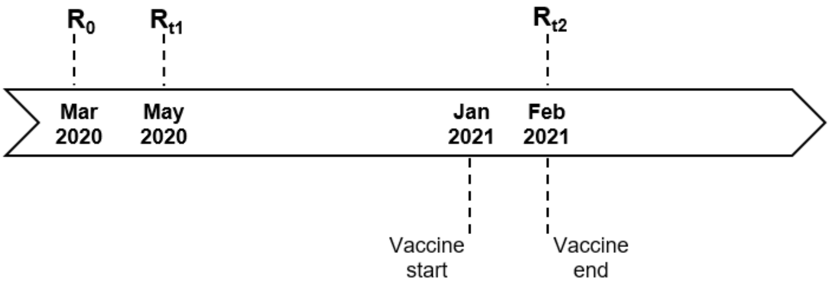

Figure S4: Schematic Illustration of the Timing of Changes in Levels of Transmission and the Introduction of Vaccination.

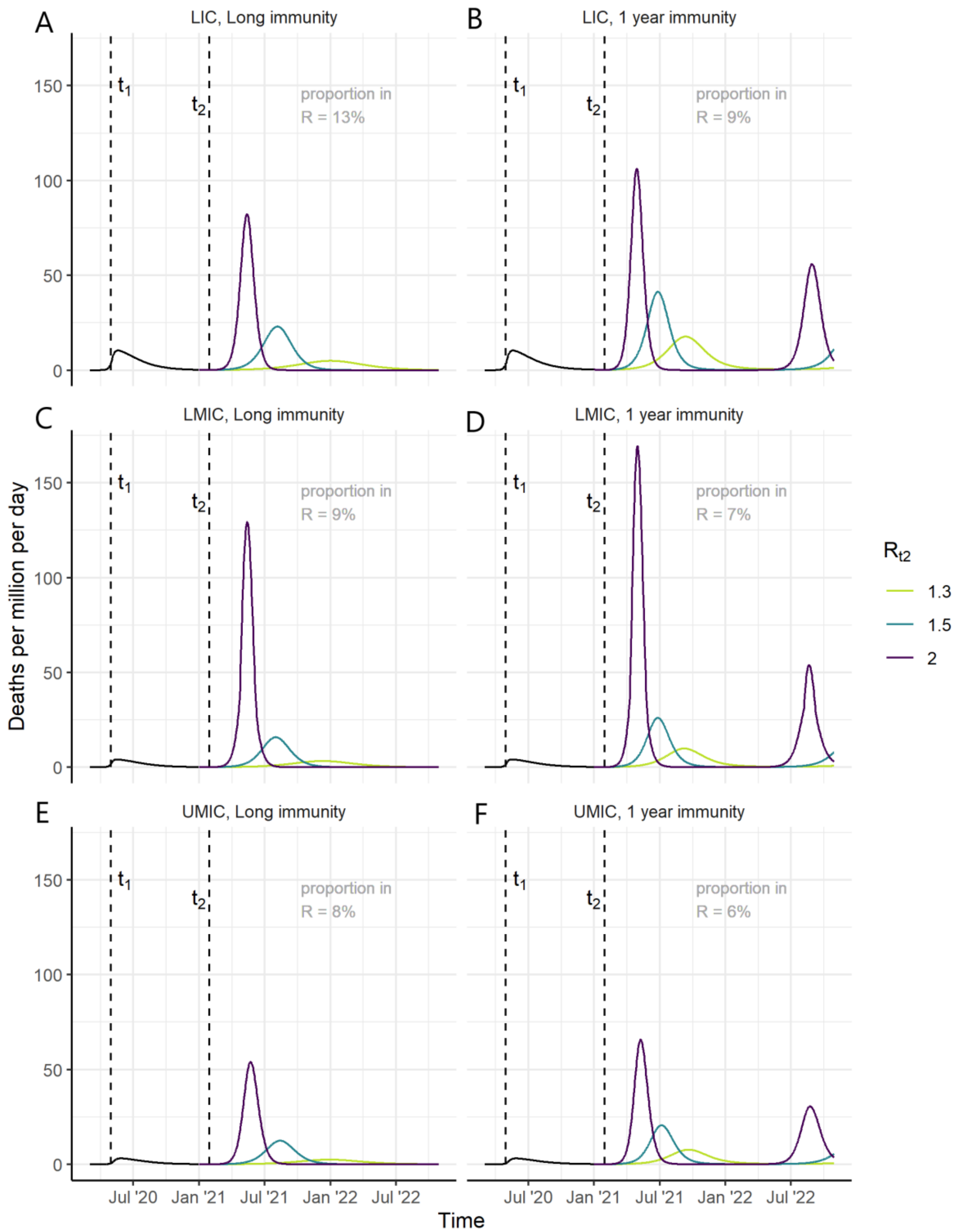

Figure S5: Scenarios for the Course of the Epidemic from 2020–2022, for Upper-Middle-, Lower-Middle- and Low-Income Country Settings (UMIC, LMIC and LIC respectively). (A, C, E) Assuming "long immunity" and (B, D, F) assuming an average duration of naturally acquired immunity of 1 year. We assume that R_0=2.5 up to time t_1 (May 2020) and that R_{t1} drops to 1.0 between time t_1 and t_2 (February 2021). From time t_2 onwards, we consider three counterfactual scenarios, R_{t2}=1.3, 1.5 and 2 shown in yellow, green and purple respectively.

DOI: https://doi.org/10.25561/82822

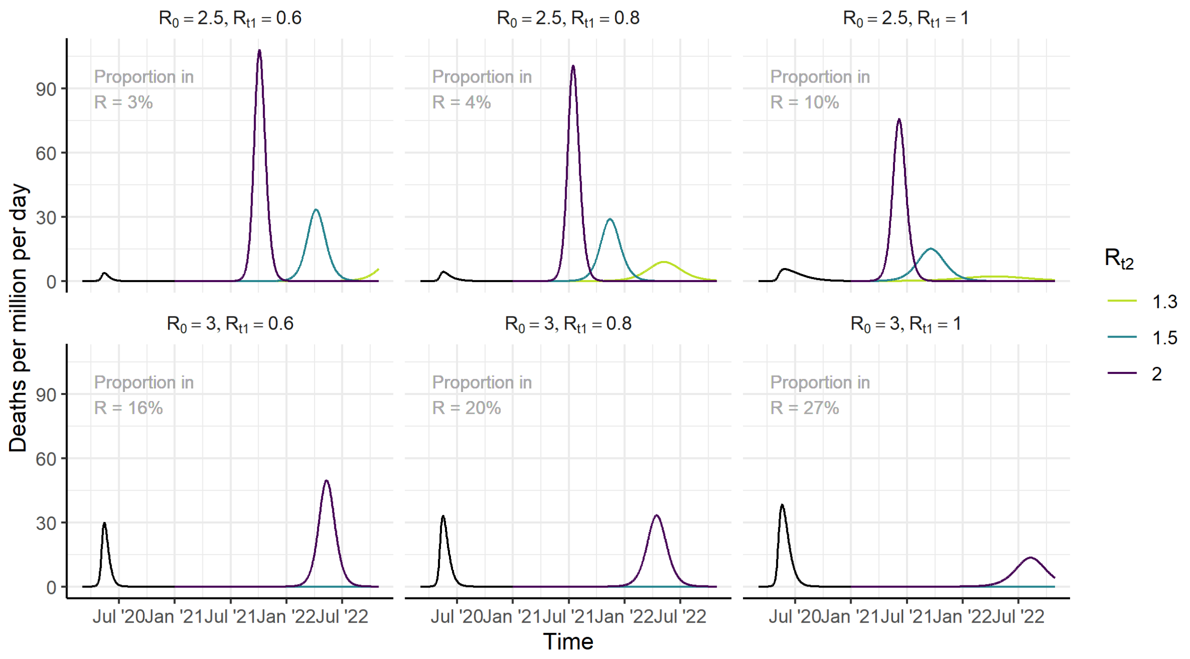

Figure S6: Scenarios for the Course of the Epidemic from 2020–2022 (counterfactual scenarios). Epidemic trajectories are shown for a high-income country setting, in the absence of a vaccine, for a range of values of R_0 (rows), R_{t1} (columns), and R_{t2} (coloured lines). The grey annotated text indicates the proportion of the population in the recovered class at February 2021. Immunity following infection is assumed to be long-term.

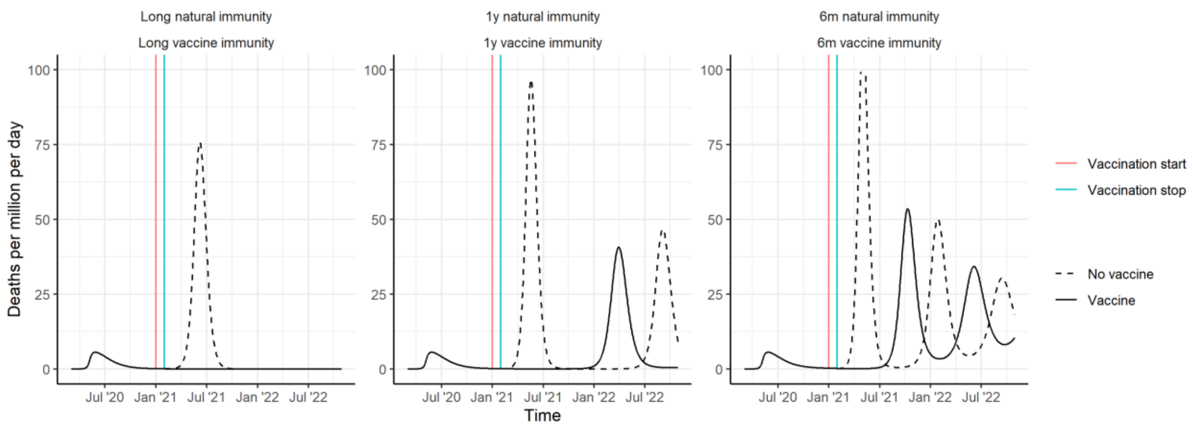

Figure S7: Epidemic Trajectories and Impact of Immunity. Epidemic scenarios are shown for the period 2020–2022, both in the absence of a vaccine (dashed black lines) and following vaccine introduction (solid black lines). Vaccine implementation over a one-month period is indicated by the red and blue vertical lines. The left plot represents the scenario where vaccine- and naturally-derived immunity are long-term, while the middle plot shows the trajectories where both durations are one year, and the right plot shows trajectories where both durations are six months. Trajectories are shown for a high-income country setting, and assuming the default transmission and vaccine parameters as in Table 1.

DOI: https://doi.org/10.25561/82822

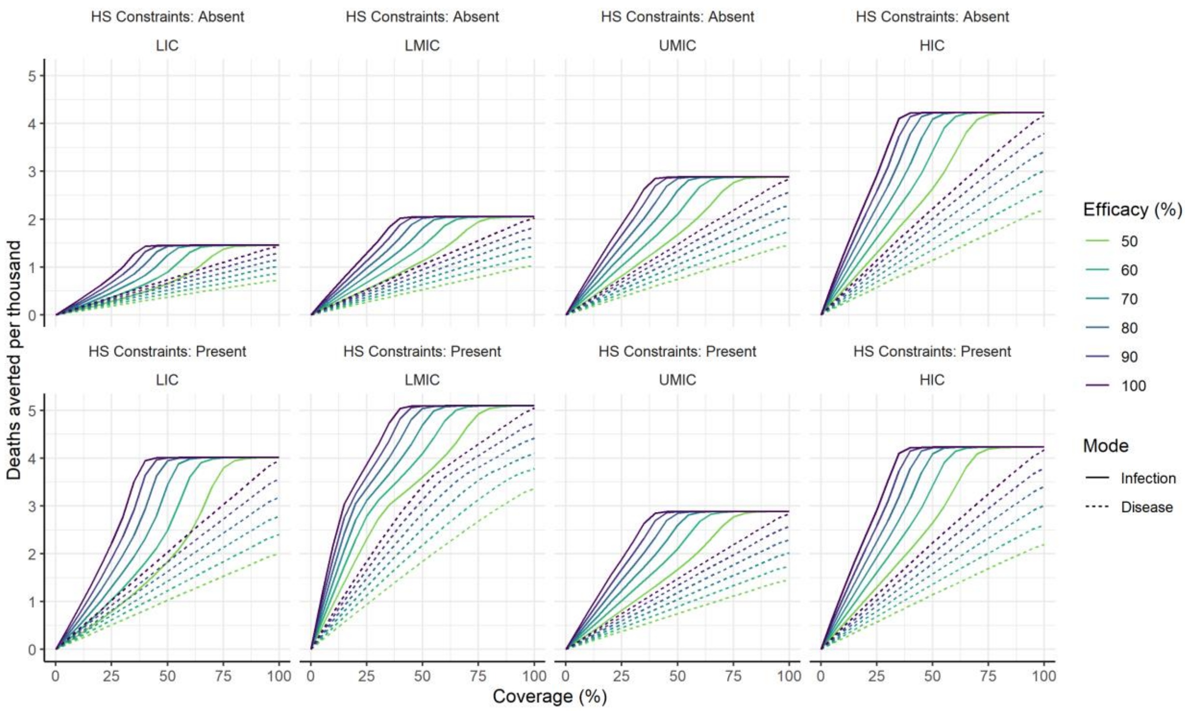

Figure S8: Vaccine Efficacy and Herd Immunity by Income Setting. Projected total deaths averted per thousand population in 2021 under the default vaccine scenarios shown in Table 1, for the four income settings (columns), and with health system constraints either absent or present (rows). The colours show different vaccine efficacy assumptions (from 50% to 100%). Solid lines represent impact for an infection-blocking vaccine; dashed lines are for a vaccine that prevents severe disease but does not reduce infection or onwards transmission.

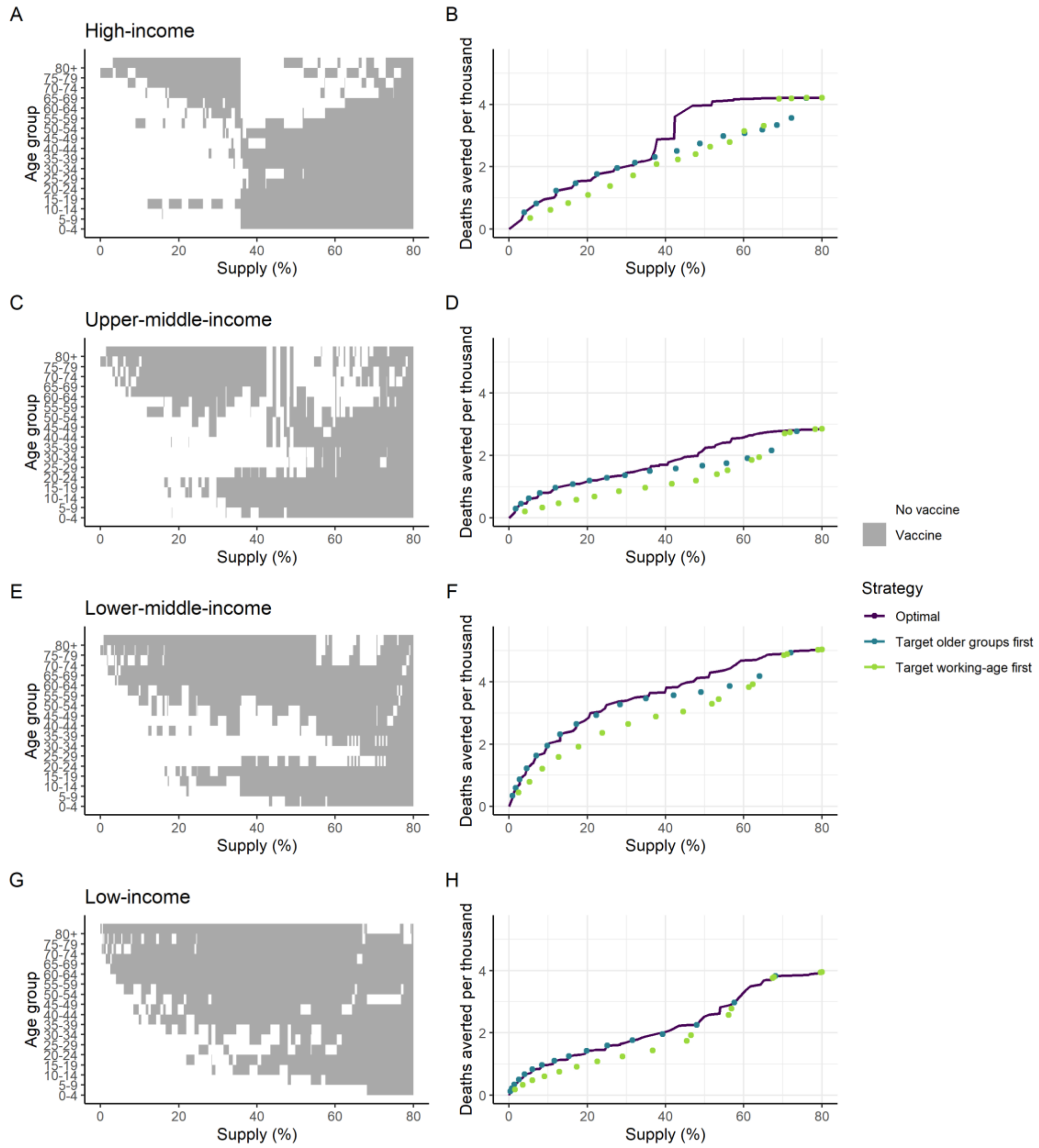

Figure S9: Sensitivity Analysis of Targeting of Vaccine Introduction; Lower Vaccine Efficacy (50%). These panels illustrate the most efficient allocation under different dose constraints, where the supply is defined as the proportion of the population able to access two doses. Panels A, C, E and G show the age groups allocated under each supply level, where the grey shaded regions indicate the age groups allocated the vaccine. Panels B, D, F and H show the efficiency frontiers expressed as deaths averted per thousand population as a function of vaccine supply. The optimal strategies from the left-hand panels are shown in purple. The turquoise shows the strategy that prioritises the older at-risk age: 80+ for the lowest coverage level, and sequentially including additional age groups (75–79, 70–74 and so on) as additional doses are available. The green strategy prioritises the working age population first (beginning with the 60–64 age group and sequentially adding younger groups), then vaccinates the elderly and children as doses become available. Health system constraints are assumed to be present. These allocations are generated using the default vaccine characteristics in Table 1.

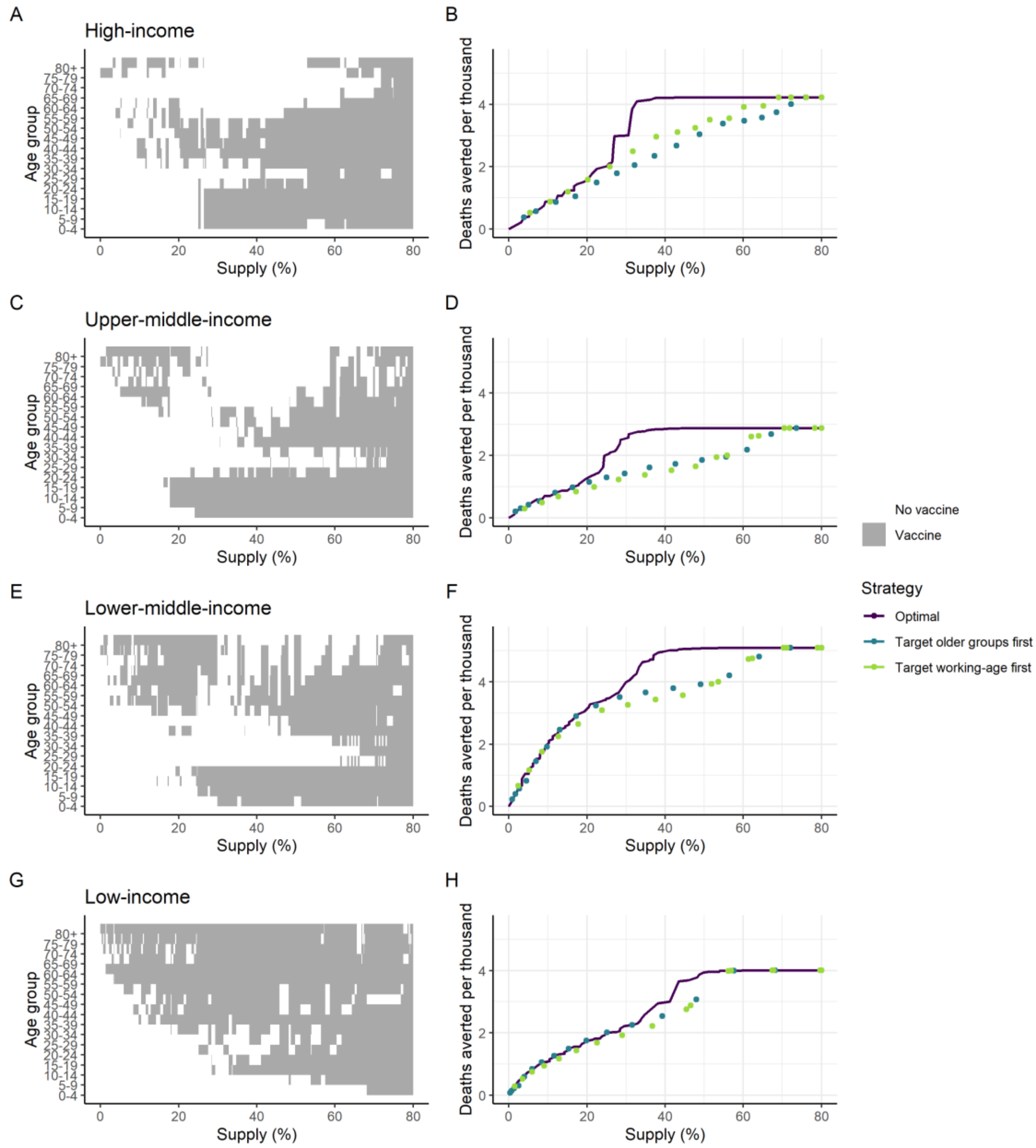

Figure S10: Sensitivity Analysis of Targeting of Vaccine Introduction; Reduced Vaccine Impact in 65+ Age Group. Vaccine efficacy was reduced in the 65+ age group to 35%. These panels illustrate the most efficient allocation under different dose constraints, where the supply is defined as the proportion of the population able to access two doses. Panels A, C, E and G show the age groups allocated under each supply level, where the grey shaded regions indicate the age groups allocated the vaccine. Panels B, D, F and H show the efficiency frontiers expressed as deaths averted per thousand population as a function of vaccine supply. The optimal strategies from the left-hand panels are shown in purple. The turquoise shows the strategy that prioritises the older at-risk age: 80+ for the lowest coverage level, and sequentially including additional age groups (75–79, 70–74 and so on) as additional doses are available. The green strategy prioritises the working age population first (beginning with the 60–64 age group and sequentially adding younger groups), then vaccinates the elderly and children as doses become available. Health system constraints are assumed to be present. These allocations are generated using the default vaccine characteristics in Table 1.

DOI: https://doi.org/10.25561/82822

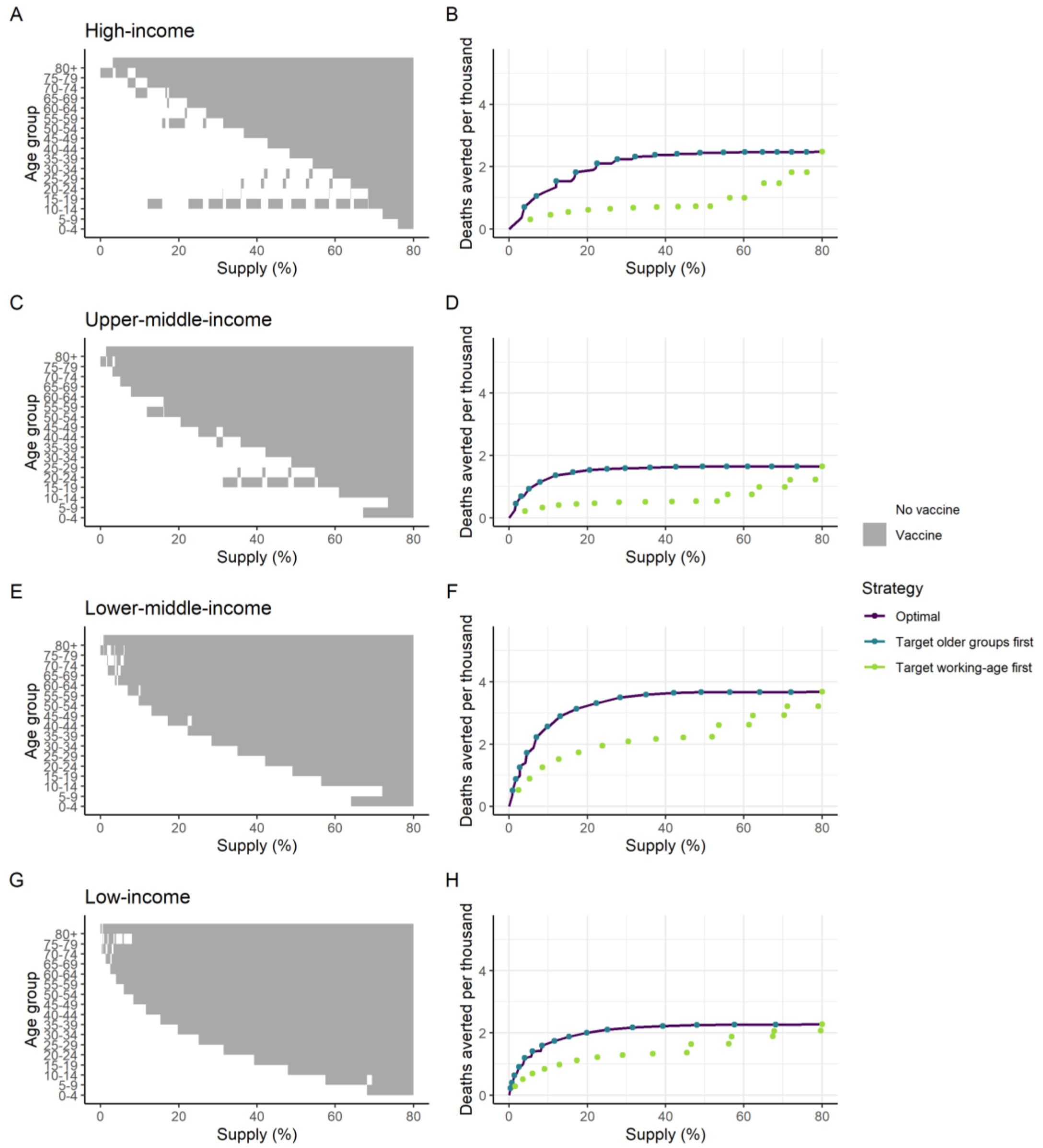

Figure S11: Sensitivity Analysis of Targeting of Vaccine Introduction; Disease-Blocking Vaccine. These panels illustrate the most efficient allocation under different dose constraints, where the supply is defined as the proportion of the population able to access two doses. Panels A, C, E and G show the age groups allocated under each supply level, where the grey shaded regions indicate the age groups allocated the vaccine. Panels B, D, F and H show the efficiency frontiers expressed as deaths averted per thousand population as a function of vaccine supply. The optimal strategies from the left-hand panels are shown in purple. The turquoise shows the strategy that prioritises the older at-risk age: 80+ for the lowest coverage level, and sequentially including additional age groups (75–79, 70–74 and so on) as additional doses are available. The green strategy prioritises the working age population first (beginning with the 60–64 age group and sequentially adding younger groups), then vaccinates the elderly and children as doses become available. Health system constraints are assumed to be present. These allocations are generated using the default vaccine characteristics in Table 1.

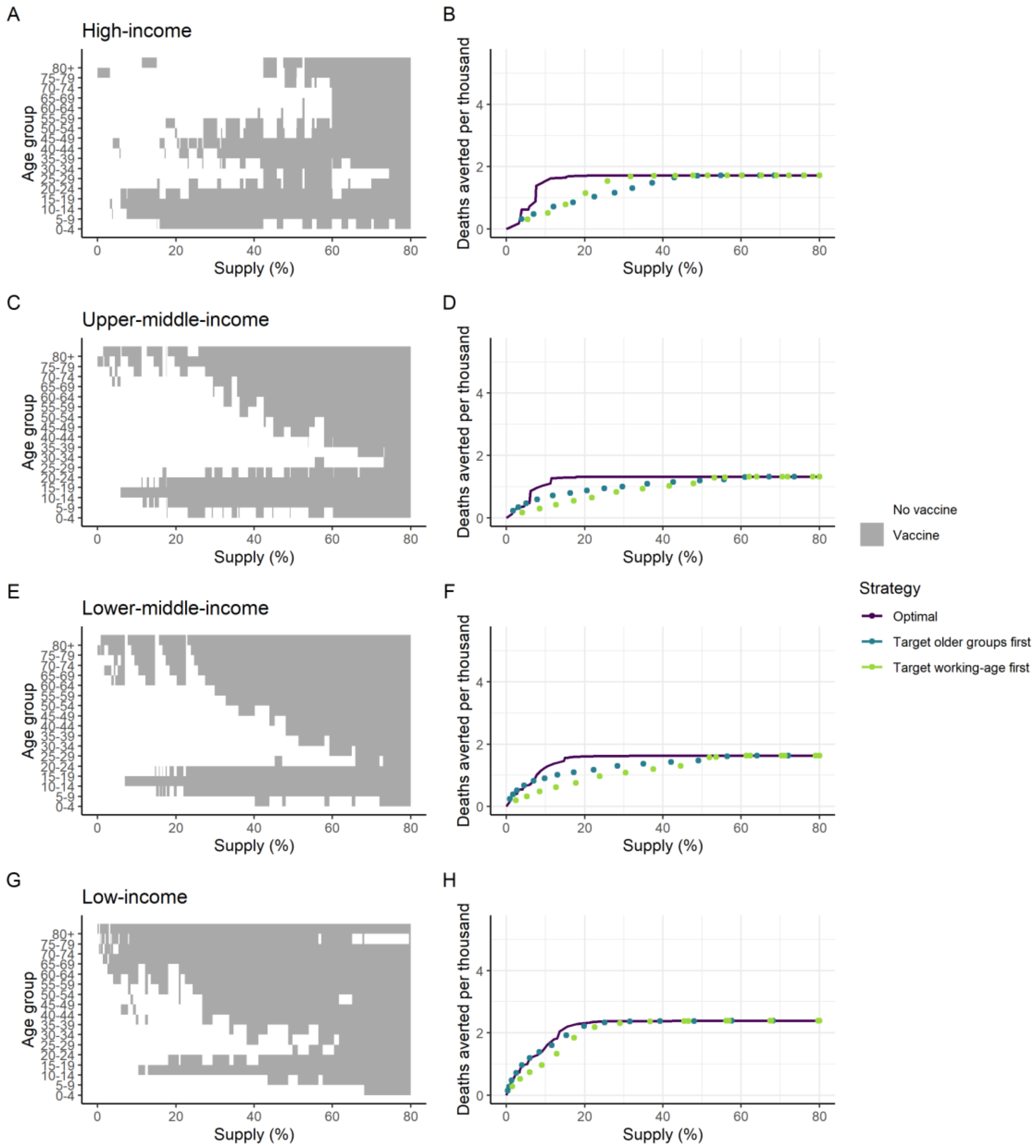

Figure S12: Sensitivity Analysis of Targeting of Vaccine Introduction; R_{t2}=1.5. These panels illustrate the most efficient allocation under different dose constraints, where the supply is defined as the proportion of the population able to access two doses. Panels A, C, E and G show the age groups allocated under each supply level, where the grey shaded regions indicate the age groups allocated the vaccine. Panels B, D, F and H show the efficiency frontiers expressed as deaths averted per thousand population as a function of vaccine supply. The optimal strategies from the left-hand panels are shown in purple. The turquoise shows the strategy that prioritises the older at-risk age: 80+ for the lowest coverage level, and sequentially including additional age groups (75–79, 70–74 and so on) as additional doses are available. The green strategy prioritises the working age population first (beginning with the 60–64 age group and sequentially adding younger groups), then vaccinates the elderly and children as doses become available. Health system constraints are assumed to be present. These allocations are generated using the default vaccine characteristics in Table 1.

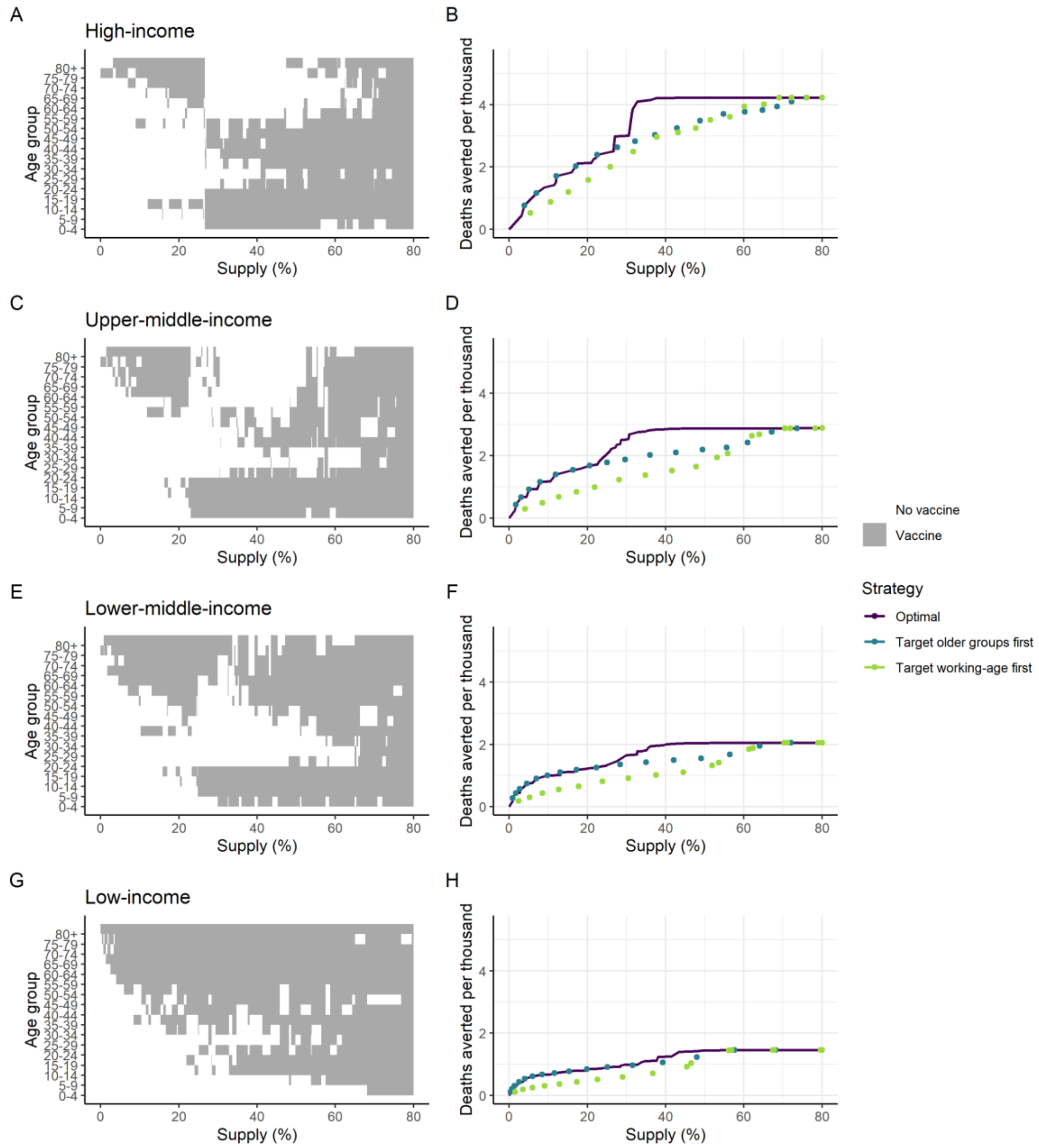

Figure S13: Sensitivity Analysis of Targeting of Vaccine Introduction; Health System Constraints Absent. These panels illustrate the most efficient allocation under different dose constraints, where the supply is defined as the proportion of the population able to access two doses. Panels A, C, E and G show the age groups allocated under each supply level, where the grey shaded regions indicate the age groups allocated the vaccine. Panels B, D, F and H show the efficiency frontiers expressed as deaths averted per thousand population as a function of vaccine supply. The optimal strategies from the left-hand panels are shown in purple. The turquoise shows the strategy that prioritises the older at-risk age: 80+ for the lowest coverage level, and sequentially including additional age groups (75–79, 70–74 and so on) as additional doses are available. The green strategy prioritises the working age population first (beginning with the 60–64 age group and sequentially adding younger groups), then vaccinates the elderly and children as doses become available. Health system constraints are assumed to be present. These allocations are generated using the default vaccine characteristics in Table 1.

DOI: https://doi.org/10.25561/82822

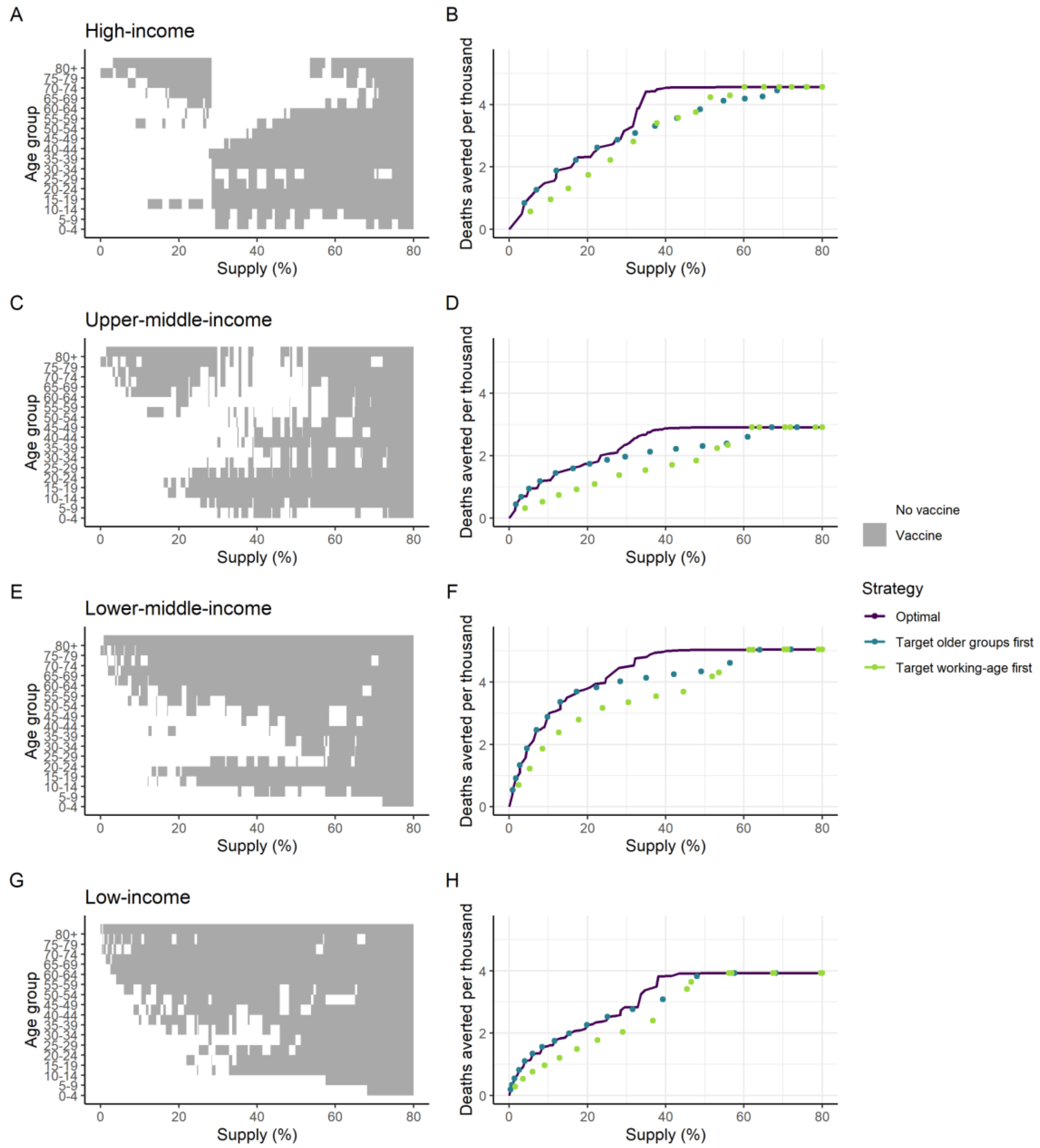

Figure S14: Sensitivity Analysis of Targeting of Vaccine Introduction; Transmission from Children Under 10 Years Reduced by 50%. These panels illustrate the most efficient allocation under different dose constraints, where the supply is defined as the proportion of the population able to access two doses. Panels A, C, E and G show the age groups allocated under each supply level, where the grey shaded regions indicate the age groups allocated the vaccine. Panels B, D, F and H show the efficiency frontiers expressed as deaths averted per thousand population as a function of vaccine supply. The optimal strategies from the left-hand panels are shown in purple. The turquoise shows the strategy that prioritises the older at-risk age: 80+ for the lowest coverage level, and sequentially including additional age groups (75–79, 70–74 and so on) as additional doses are available. The green strategy prioritises the working age population first (beginning with the 60–64 age group and sequentially adding younger groups), then vaccinates the elderly and children as doses become available. Health system constraints are assumed to be present. These allocations are generated using the default vaccine characteristics in Table 1.

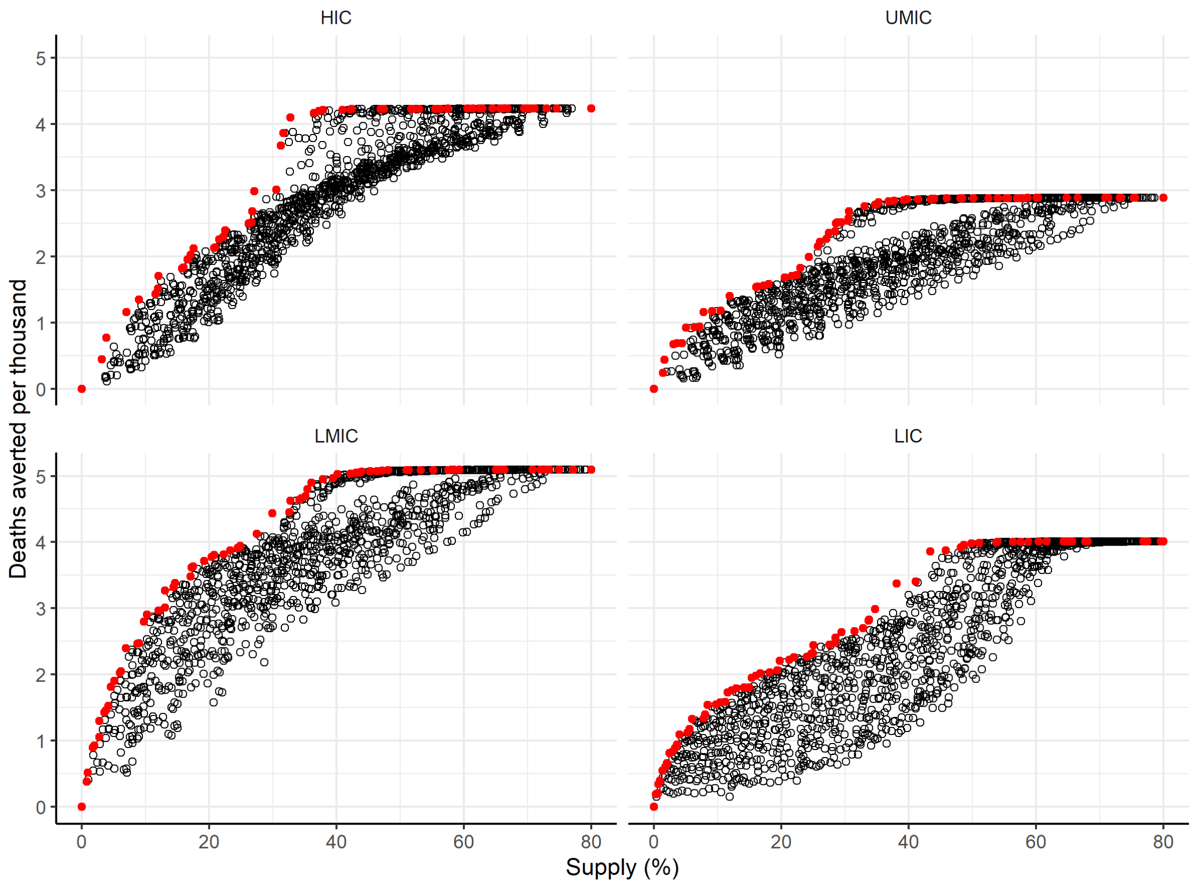

Figure S15: Efficiency Frontier for the Age Targeting of a Vaccine within each Income Setting. The black circles each represent a unique age targeting strategy, for each income setting, for increasing availability of doses on the x-axis, versus impact in terms of deaths averted per thousand population on the y-axis. The red points represent the most efficient (non-dominated) age-targeting strategies, or the maximum deaths averted as the vaccine supply is increased. These red points correspond to the age targeting strategies shown in Figure 4C, E, J and I, and the Optimal allocation strategy in Figure 4D, F, H and J.

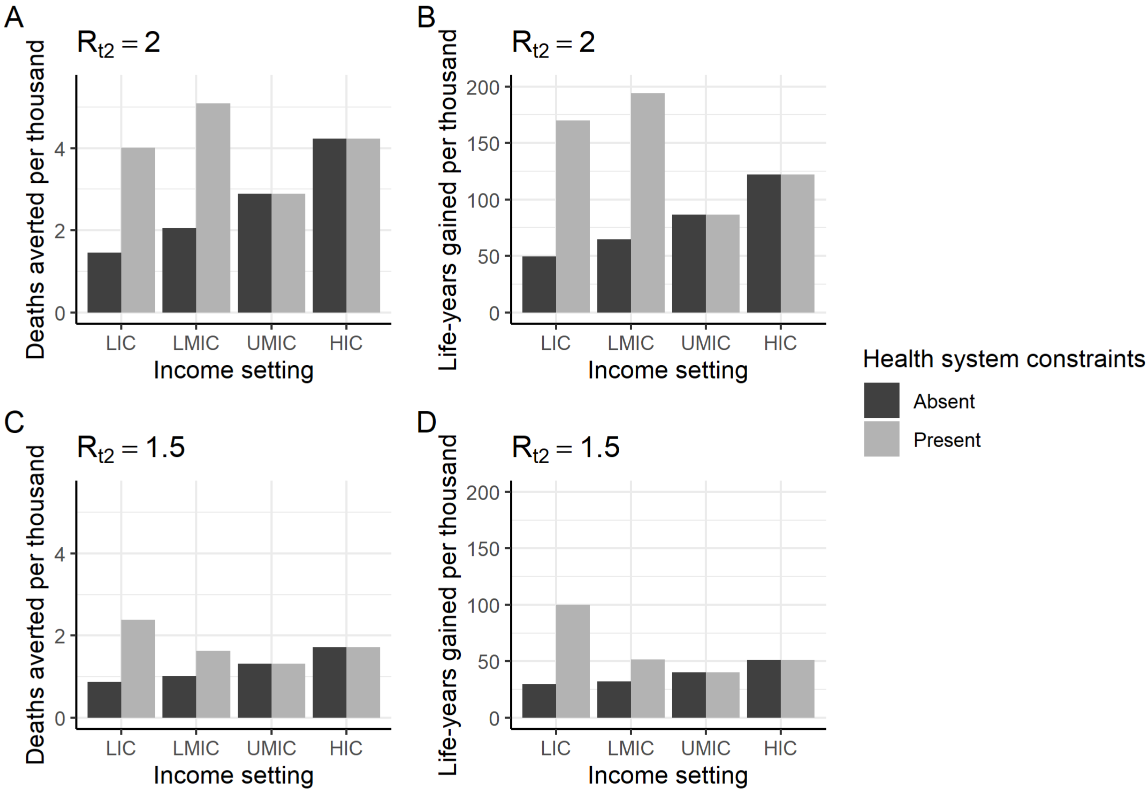

Figure S16: Vaccine Impact by Income Setting and Level of NPIs at Vaccine Introduction. Deaths averted (A, C) and life-years gained (B, D) per thousand population in 2021 for each income setting (x-axis), where health systems are either unconstrained (dark grey) or constrained (light grey), and for R_{t2}=2 (default value, upper row) and R_{t2}=1.5 (lower row). Default vaccine parameters are in Table 1.

2. Additional Tables

Table S1: Parameter Descriptions and Values. The parameters for vaccination are described in Table 1. Reproduced from Walker et al.[1]

Parameter	Symbol	Value	Description
Epidemiological Parameters			
Transmission parameter	β	-	Calculated from R_0
Basic reproduction number	R_0	3.0 (2.3, 3.5)	Estimated from European data consistent with a doubling time of 3.5 days (5 days and 3 days for R_0=2.3 and 3.5 respectively)
Mean Latent Period	$\frac{1}{\alpha}$	4.6 days	Estimated at 5.1 day. The last 0.5 days are incorporated in the infectious periods to capture pre-symptomatic infectivity
Mean Duration of Mild Infection	$\frac{1}{\gamma_1}$	2.1 days	Incorporates 0.5 days of infectiousness prior to symptoms. In combination with mean duration of severe illness this gives a mean serial interval of 6.75 days.
Mean Duration of Severe Infection Prior to Hospitalisation	$\frac{1}{\gamma_2}$	4.5 days	Mean onset-to-admission of 4 days based on unpublished analysis of data from the ICNARC study. Includes 0.5 days of infectiousness prior to symptom onset.
Mean Duration of Hospitalisation for non-critical cases if survive	$\frac{1}{\gamma_{3,1}}$	9.5 days	Based on unpublished analysis of data from the ICNARC study.
Mean Duration of Hospitalisation for non-critical cases if die	$\frac{1}{\gamma_{3,0}}$	7.6 days	Based on unpublished analysis of data from the ICNARC study.
Mean Duration in ICU if survive	$\frac{1}{\gamma_{4,1}}$	11.3 days	Based on data from the ICNARC study adjusted for censoring.
Mean Duration in ICU if die	$\frac{1}{\gamma_{4,0}}$	10.1 days	Based on data from the ICNARC study adjusted for censoring.
Mean Duration in Recovery after ICU	$\frac{1}{\gamma_5}$	3.4 days	Based on unpublished analysis of data from the ICNARC study.
Mean duration of naturally-acquired immunity	$\frac{1}{\rho}$		
Fatality rate	$\mu(a)$	-	Age-dependent - see Walker et al.[1]
Hospitalisation rate	$\phi(a)$	-	Age-dependent - see Walker et al.[1]

Table S2: Global Allocation of Vaccine Doses for both Non-Optimised Scenarios. Here we assume that limited countries within each income setting are allocated doses at high (80%) coverage, rather than all countries being allocated doses at a lower level of coverage as in Table 2. The global vaccine supply was assumed to be constrained to 2 billion doses, with a two-dose schedule and 15% buffer and wastage (resulting in 0.85 billion vaccine courses available).

Allocation strategy		**Income setting**	**Target age group**	**Deaths averted per million**	**Deaths averted per 100 fully vaccinated persons**	**Total deaths averted per million global population**	**Total deaths averted per 100 fully vaccinated persons**
Allocated to limited countries at 80% coverage	Income groups receive doses in proportion to population	HIC	all	588	0.529	561	0.505
		UMIC	all	401	0.36		
		LMIC	all	708	0.637		
		LIC	all	558	0.502		
	Income groups receive doses in proportion to population, targeted first to 65+, then 15-64 age groups	HIC	65+	1319	1.186	1684	1.515
		UMIC	65+	1156	1.475		
		LMIC	65+	1820	3.991		
		LIC	65+	810	3.266		
		HIC	15-64	0	0		
		UMIC	15-64	120	0.365		
		LMIC	15-64	497	0.757		
		LIC	15-64	524	0.607		
	Income groups receive doses in proportion to population in 65+ age group, targeted first to 65+, then 15-64 age groups	HIC	65+	2021	1.186	1719	1.547
		UMIC	65+	1156	1.475		
		LMIC	65+	1820	3.991		
		LIC	65+	810	3.266		
		HIC	15-64	541	0.681		
		UMIC	15-64	134	0.365		
		LMIC	15-64	161	0.757		
		LIC	15-64	70	0.607		
	Allocated first to high-income countries	HIC	all	3709	0.529	588	0.529
		UMIC	all	0	0		
		LMIC	all	0	0		
		LIC	all	0	0		
	Allocated first to low-income and lower-middle-income countries	HIC	all	0	0	680	0.612
		UMIC	all	0	0		
		LMIC	all	1513	0.637		
		LIC	all	1192	0.502		
	Receive doses in proportion to population, plus additional 1.15 b doses to HIC and 1.1 b doses to MIC	HIC	all	2720	0.529	1204	0.510
		UMIC	all	696	0.36		
		LMIC	all	1219	0.637		
		LIC	all	558	0.502		

Table S3: Optimised Global Allocation of Vaccine Doses for Different Assumptions about Vaccine Characteristics, Transmission, and Health System Constraints.

Parameter assumptions	Income setting	Deaths averted per million	Deaths averted per 100 fully vaccinated persons	Total deaths averted per million global population	Total deaths averted per 100 fully vaccinated persons
Default	HIC	2665	1.306	2204	1.882
	UMIC	904	1.772		
	LMIC	3444	2.214		
	LIC	1520	1.72		
Lower vaccine efficacy (50%)	HIC	1962	0.893	1536	1.311
	UMIC	460	1.286		
	LMIC	2549	1.552		
	LIC	961	1.069		
Reduced vaccine efficacy (scaled by 50%) in 65+ years population	HIC	2578	1.245	1725	1.473
	UMIC	53	1.062		
	LMIC	3227	1.576		
	LIC	836	1.345		
Mode of action of vaccine as disease-blocking only	HIC	1672	1.141	1971	1.682
	UMIC	1082	1.477		
	LMIC	2992	2.019		
	LIC	1737	1.45		
NPIs maintained at higher level following vaccine introduction (such that R_{t2}=1.5)	HIC	1513	1.548	1383	1.181
	UMIC	1115	1.155		
	LMIC	1390	1.111		
	LIC	2313	1.138		
Health system constraints absent	HIC	4128	1.209	1455	1.242
	UMIC	1403	1.17		
	LMIC	723	1.523		
	LIC	545	1.163		
Reduced infectiousness in children younger than 10 years	HIC	2807	1.353	2258	1.928
	UMIC	1060	1.618		
	LMIC	3276	2.565		
	LIC	1989	1.371		

Table S4: Sensitivity Analysis for the Fixed Global Vaccine Allocation Scenarios.

	Sensitivity Analysis Total deaths averted per million global population (Total deaths averted per 100 fully vaccinated people)					
	Lower vaccine efficacy (50%)	Reduced vaccine efficacy (scaled by 50%) in 65+ years population	Mode of action of vaccine as disease-blocking only	NPIs maintained at higher level following vaccine introduction (such that R_{t2}=1.5)	Health system constraints absent	Reduced infectiousness in children younger than 10 years
Income groups receive doses in proportion to population	650 (0.584)	871 (0.784)	399 (0.359)	696 (0.626)	494 (0.445)	999 (0.899)
Income groups receive doses in proportion to population, targeted first to 65+, then 15-64 age groups	1227 (1.105)	1048 (0.943)	1511 (1.36)	840 (0.756)	1097 (0.987)	1910 (1.719)
Income groups receive doses in proportion to population in 65+ age group, targeted first to 65+, then 15-64 age groups	1200 (1.08)	951 (0.856)	1527 (1.374)	873 (0.785)	1235 (1.112)	1847 (1.662)
Allocated first to high-income countries	649 (0.584)	671 (0.603)	347 (0.312)	273 (0.246)	671 (0.603)	723 (0.651)
Allocated first to low-income and lower-middle-income countries	906 (0.815)	1193 (1.073)	535 (0.481)	752 (0.677)	335 (0.302)	1253 (1.128)
Receive doses in proportion to population, plus additional 1.15 b doses to HIC and 1.1 b doses to MIC	1379 (0.584)	1921 (0.813)	824 (0.349)	1212 (0.513)	1266 (0.536)	2120 (0.898)

DOI: https://doi.org/10.25561/82822

3. Methods for Vaccine Age-Targeting

For the global optimisation of vaccine allocation by income setting and age target, we run the simulation for the vaccine distributed to combinations of 5-year age groups from 0–4 years up to 7–79 years and 80+ years. Rather than simulating impact for every possible combination of age groups targeted, we construct the parameter space such that the vaccine could be targeted to up to two distinct contiguous groups, or rather up two non-overlapping age groups that are each comprised of any number of consecutive 5-year groups. The age group combinations are depicted in Figure S17.

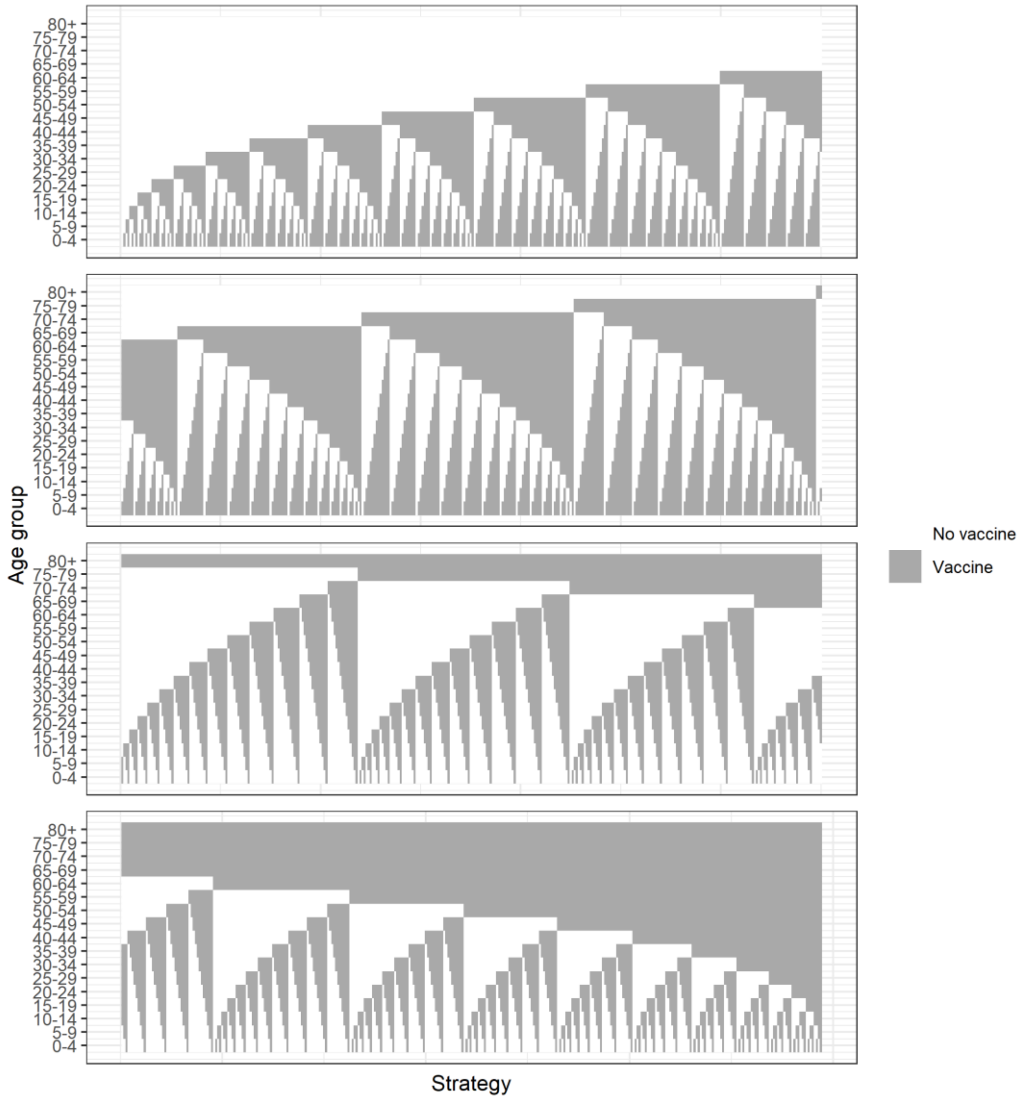

Figure S17: Illustration of 5-Year Age Group Combinations.

4. References

1 Walker PGT, Whittaker C, Watson OJ, *et al.* The impact of COVID-19 and strategies for mitigation and suppression in low- and middle-income countries. *Science (80-)* 2020; **422**: eabc0035.