Altruistic Vaccine Stockpile Sharing For Selfish Objectives

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Abstract

The COVAX program aims to provide global equitable access to COVID-19 vaccines, which have been proven to reduce cases and fatalities. However, vaccine nationalism by wealthy nations has created roadblocks to this aim in poorer nations, with only 19% of the population in Africa having received one or more doses, resulting in widespread infections and possible appearance of new strains. Travel bans and lockdowns cannot be imposed indefinitely and the combination of circulating and imported cases can trigger new outbreaks in vaccine-rich nations when stringent measures are lifted. Here, we evaluate whether vaccine stockpile sharing can have beneficial effects on vaccine-rich nations even when such nations act with purely selfish objectives. We explore this by considering a scenario with two interconnected nations (due to migration, travel etc.), one of which has a stockpile of vaccines and another which is vaccine-deficient. Assuming the vaccine-rich nation acts based on the motivation of reducing fatalities in its own region, we find that sharing a significant fraction of a vaccine stockpile is optimal, even given selfish objectives. Mechanistically, we find that when vaccination rates are sufficiently slow that sharing a vaccine stockpile reduces the intensity of outbreaks in a vaccine-poor nation, thereby reducing import of new cases. Despite acting selfishly, sharing vaccines by a vaccine-rich nation has a key altruistic benefit: significantly reducing transmission and fatalities in the vaccine-poor nation. We also propose a hybrid sharing policy which has a negligible effect on the fatalities in the donor nation compared to the optimal policy, but greatly reduces fatalities in the recipient nation. These findings provide additional incentive for nations with an extensive vaccine stockpile to share with other nations - doing so can reduce the scope and intensity of future outbreaks.

1 Introduction

Vaccines have shown to be effective in reducing new infections and hospitalizations [1, 2], however, the availability of doses across nations has been highly non-uniform [3]. While sharing vaccines between nations to increase coverage is now seen as a global imperative [4], most wealthy nations have not initiated vaccine sharing campaigns that would promote vaccine equity in neighboring countries andor worldwide. Vaccine sharing can reduce the intensity of outbreaks, reduce the risk of the emergence of variants of concern, and reduce the risk of case importation when stringent regulations are relaxed in a donor country [5]. However, vaccine sharing comes with a cost: reducing the availability of vaccines for the donor nation. This reduction is perceived to lead to greater infections, hospitalizations, and fatalities in donor countries – and may also come with political costs for decision-makers who propose that nations acts altruistically to share their vaccine stockpiles.

One way to assess the costs and benefits of vaccine stockpile sharing is to consider the potential impacts on a donor country given coupled models of epidemic dynamics. A recent paper [6] studied the efficacy of vaccine sharing between two nations with extensive travel between the donor and recipient nation. Epidemic dynamics within each country were coupled through the occasional importation of

cases and/or the travel of individuals to and from the donor country to the recipient country (where they could be infected) and back again (where they could accelerate disease transmission). This study concluded that the greatest reduction in fatalities within the vaccine-rich nation occurred in the absence of sharing. This epidemic model analysis included a time-dependent sharing protocol while assuming that vaccination rates were high, e.g., the eligible population would be fully vaccinated within 50 days. In practice, vaccination coverage has increased far slower, e.g., in the US, only 60% of the population is considered fully vaccinated more than one year after the widespread availability of vaccines [7]. As a result, here we consider a two-nation epidemic model with the potential for a donor (vaccine-rich) country to share vaccines with a recipient (vaccine-poor) country. In doing so, we seek the optimal sharing policy while maximizing a selfish objective - reducing fatalities only within the donor country. We also consider a broader range of realized vaccination rates, based on data from USA (where ~62% of the population was fully vaccinated in a period of 1 year), UK (~69% were fully vaccinated in 1 year), and a global average of ~46% being fully vaccinated in a year [8]. Despite the selfish objective, we find that there are a broad range of vaccine uptake rates and cross-nation travel rates in which the the optimal policy is to share vaccines - often a substantial fraction of a vaccine stockpile. As we show, sharing vaccines can reduce the fatalities in the donor country with the added benefit that acting selfishly induces altruistic sharing that also curbs the spread of COVID-19 in the recipient nation.

2 Vaccine sharing problem

We consider two countries, A and B, each confronting a COVID-19 outbreak in which one country (A) has a vaccine stockpile and the other country (B) does not. The outbreak is modelled using SEIRV (Susceptible - Exposed - Infected - Recovered - Vaccinated) dynamics. The system dynamics of the countries are coupled and active infections in one country can cause infections in the other country. Further, country A has the option of donating a part of its vaccine stock to country B. This vaccine sharing can only be done once at the start of the outbreak - between A (the donor country) and B (the recipient country).

The objective of the selfish, optimal vaccine sharing policy is to minimize fatalities in the donor country. The epidemic dynamics between countries are coupled. Here, we explore optimal policies as a function of epidemiological parameters as well as two features of the two-nation problem: (i) the epidemic coupling constant; (ii) the rate of vaccine uptake in the donor country. Increase in the epidemic coupling constant makes it more likely that infections in the recipient country lead to new cases in the donor country (and vice-versa). The vaccine uptake rate controls the rate at which a donor country can potentially use its vaccine stockpile; and we focus on limits in which the rate of vaccine uptake (on the order of a year) is slower than that of typical outbreak dynamics (i.e., on the order of months). In all cases the objective of the donor country is to minimize fatalities in its own country. Later we relax this strict assumption to find adjacent (nearly-optimal) solutions that provide substantial benefit to recipient nations. Full details of the dynamic model and optimization function are available in the Supplementary Information.

3 Results

We consider the two countries to have an initial population of 10^7 with 500 initial infections in which country A has enough vaccines to fully vaccinate 7×10^6 individuals. The optimal vaccine sharing fraction μ^* is the the value which minimizes fatalities in A, irrespective of the effect in B. We explore the dependence of the optimal policy with respect to the daily vaccination rate. λ and the epidemic coupling constant. κ in the heatmap shown in Fig. 1. For $\kappa \leq 10^{-6}$, the optimal vaccine sharing fraction is 0 if the vaccination rate is sufficiently high. These findings are consistent with the results reported in [6] - the rationale is that it is more effective to rapidly immunize nearly the entire population than to share and reduce the importation of cases. However, when vaccination rates within A are slow (e.g., less than 0.19%/day, equivalent to 70%/year), then the optimal vaccine sharing fraction is positive for all epidemic coupling constants studied. When the epidemic coupling constant between the two countries is stronger, then it is beneficial to donate more vaccines to country B. From the heatmap, we find that the optimal fraction is negatively correlated with the vaccination rate. Moreover, we also find a critical transition: if the vaccination rate is low, then the optimal policy is to share vaccines

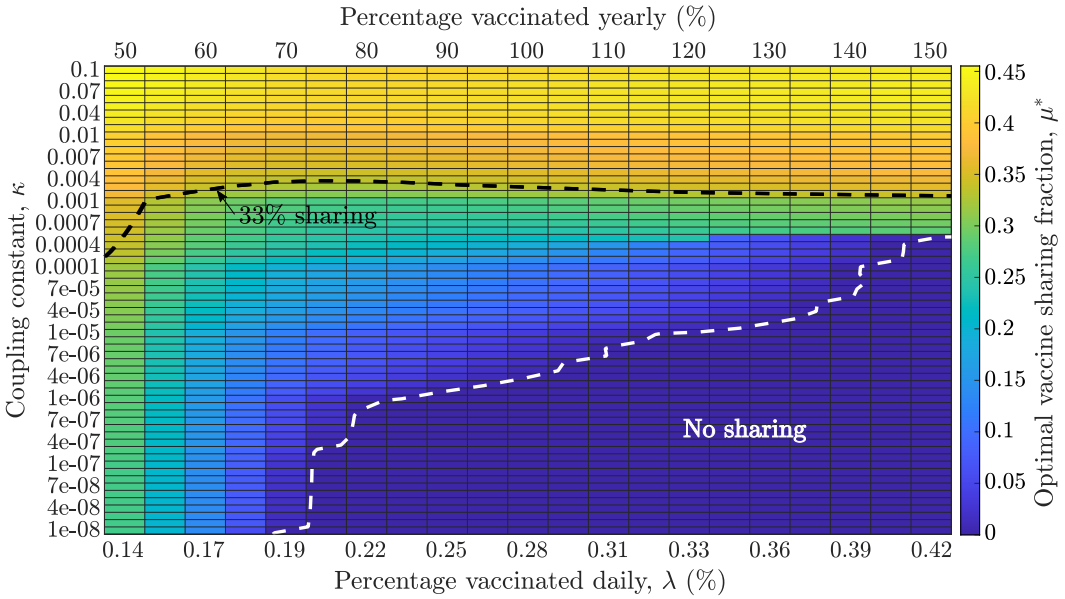

Figure 1: Dependence of the optimal fraction of vaccines (μ^*) to be donated as a function of the vaccination rate, λ (x-axis) and the epidemic coupling coefficient, κ (y-axis). For very low values of κ and moderate to high vaccination rates, the optimal sharing fraction is 0. For all other values, the optimal vaccination donation fraction from country A to country B is positive, increasing with the epidemic coupling constant and the realized vaccination rate in country A. The black dashed line shows a level curve of $\mu^* = 1/3$, while the white dashed line demarcates the region where $\mu^* = 0$, that is, there is no vaccine sharing.

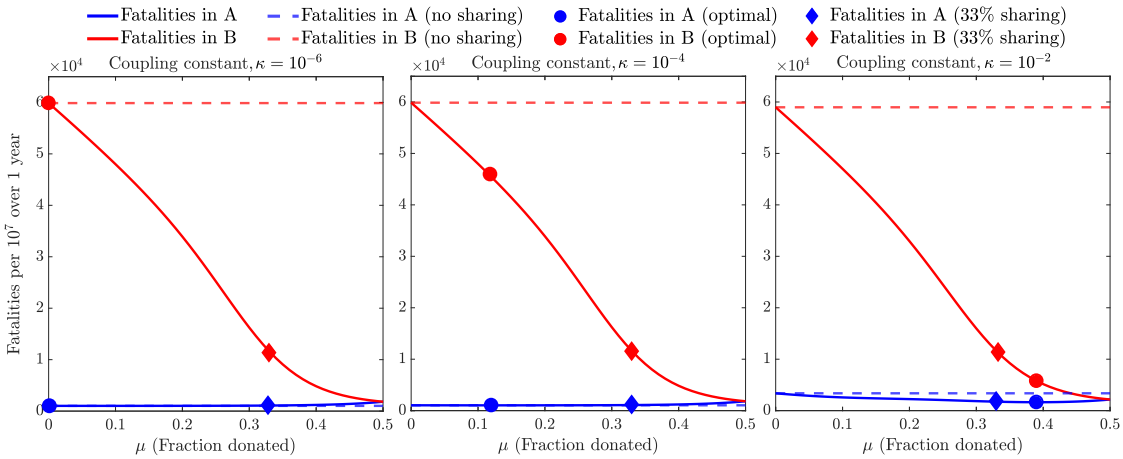

Figure 2: Model-based fatalities per 10^7 over 1 year in countries A and B for different values of vaccines donated from A to B (μ). The value of μ which minimizes the fatalities in country A is termed the 'optimal policy'. The simulation is run for low, medium and high epidemic coupling constants, κ (with $\kappa \in \{10^{-6}, 10^{-4}, 10^{-2}\}$) and the daily vaccination rate is held fixed at 0.28% of the total population in all three panels. The optimal fraction for every κ is marked on the corresponding plot with a circle, along with the fatalities in countries A and B for a 33% sharing policy (diamond) and the no-share policy (dashed line).

with country B even for very low epidemic coupling constant values.

Fig. 1 provides the optimal vaccine sharing fraction for different settings, however, it does not quantify the efficacy of implementing such a policy on epidemic outcomes. To do so, we quantify the fatalities in A and B when no vaccines were shared, i.e. $\mu = 0$ and compare these baseline levels of fatalities to simulated epidemic outcomes for different values of μ. Fig. 2 shows the deaths per

Epidemic coupling constant, κ	Fatality - no sharing		Fatality - optimal sharing		Fatality - 33% sharing	
	Country A	Country B	Country A	Country B	Country A	Country B
10^{-6}	1.02×10^3	5.99×10^4	1.02×10^3	5.99×10^4	1.08×10^3	1.11×10^4
10^{-4}	1.04×10^3	5.99×10^4	1.03×10^3	4.63×10^4	1.09×10^3	1.11×10^4
10^{-2}	3.37×10^3	5.90×10^4	1.64×10^3	0.64×10^4	1.73×10^3	1.12×10^4

Table 1: Fatality per 10^7 over 1 year in country A and B for different sharing policies - no-sharing, optimal and 33% sharing. The daily vaccination rate is set as 0.28% of the total population. This table lists the total fatalities for all three policies (no-sharing, optimal and hybrid) shown in Fig. 2.

10^7 individuals in both countries for different values of as a function of the vaccine sharing fraction, μ and given three scenarios for κ (low, medium and high epidemic coupling constant) with a fixed daily vaccination rate of 0.277% of the total population (equivalent to a vaccination rate that would vaccinate the entire eligible population in one year). For all values of κ, sharing a small fraction of vaccines ($\mu > 0$) rapidly reduces the fatalities in B and either decreases the fatalities in A ($\kappa = 10^{-2}$) or has a negligible adverse effect ($\kappa = 10^{-4}, 10^{-6}$). For $\kappa = 10^{-6}$, the optimal sharing fraction is $\mu^* = 0$, hence the optimal policy is the same as the no-share policy. For $\kappa = 10^{-4}$, the fatality reduction in A is negligible, but there is a ~24% reduction in fatalities in B given an optimal sharing fraction of μ^*~0.11. Lastly, for $\kappa = 10^{-2}$, the optimal policy is to share μ^*~0.38, or more than one-third of the donor nation's vaccine stockpile. Compared to the no-share policy ($\mu = 0$), there is a ~50% and ~90% reduction in fatalities in countries A and B respectively. By donating a part of the vaccine stock to B, the infections of individuals in country B are reduced which in turn reduces the cross-infections of individuals in country A. However, this will also reduce the population of country A which is vaccinated. The magnitude of these competing factors is dependent on the epidemic coupling constant κ, which explains the shift towards a higher sharing policy as κ increases.

The prior optimal sharing analysis revealed an interesting feature: deviating from the optimal policy led to minimal changes in fatalities in A in both the high and medium epidemic coupling scenarios (see Fig. 2). This suggests that using a higher than optimal fraction (when μ^* is either zero or a small fraction) would likely have negligible effects for country A, but confer significant benefits for country B. Based on this observation, we propose a hybrid policy, which is the same as the optimal policy when the optimal vaccine sharing fraction is high, and has a fixed, non-zero vaccine sharing fraction when the optimal is low. Let $\hat{\mu}$ represent this hybrid strategy, which we set as $\hat{\mu} = \max\{\mu^*, 1/3\}$. To check the efficacy of the optimal and hybrid policies, we compare the reduction in fatalities in countries A and B using these policies against the no-sharing policy. Fig. 3 shows that when the hybrid policy is compared to the no-sharing policy, then the fatalities in A are increased by less than 10% when the vaccination rate is high ($\geq 75\%$) and the epidemic coupling constant is low. However, for these scenarios, there is a large reduction in fatalities in B ($\geq 70\%$), which is greater than the corresponding reduction achieved by the optimal policy. Thus, by slightly relaxing the requirement that A have a strictly selfish policy, vaccine sharing can lead to dramatic changes in fatalities in the recipient country with minimal impacts on the donor country. Similar results are found on a continuum of scenarios when varying both the vaccine uptake rate and the epidemic coupling constant (see Figs. S1 and S2).

4 Discussion

Travel between countries each experiencing an epidemic can lead to enhanced transmission and mortality despite controlling local conditions. In order to evaluate the impact of vaccine sharing on epidemic outcomes, we explored the optimal sharing policy between a donor and recipient country. Even with a selfish objective - i.e. minimizing fatalities in the donor country, significant reductions (~20%) can be observed for a moderately high epidemic coupling constant. This supports the notion that a selfish objective can lead to an altruistic policy. Further, by providing some vaccines to the recipient country, the outbreak and deaths in a recipient nation can be reduced.

The optimal policy of vaccine allocation is dependent on the epidemic coupling constant and the daily vaccination rates. A very small coupling constant, κ implies the two countries have nearly independent dynamics. Such a situation can occur if travel-bans have been implemented. In this case, using all vaccines in the donor country provides maximum benefit in minimizing deaths in the

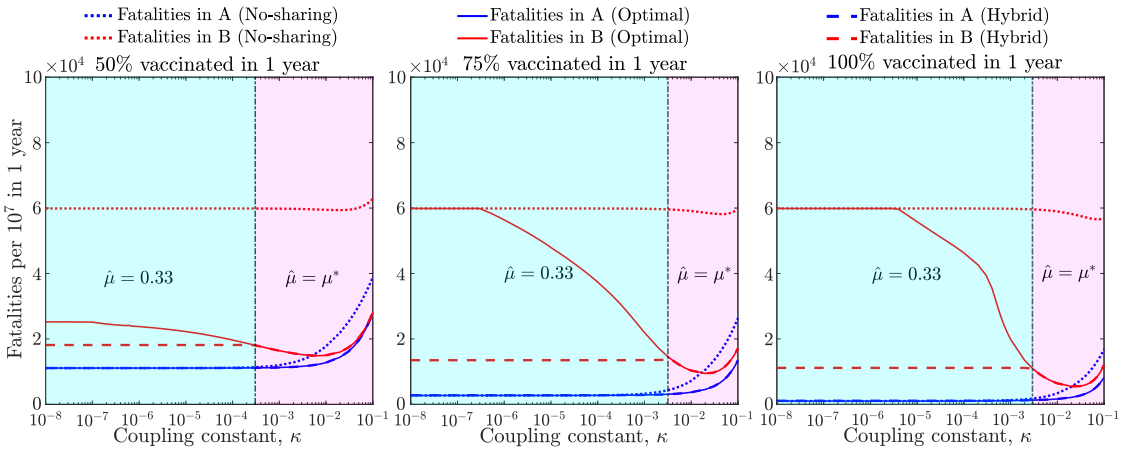

Figure 3: Fatalities per 10^7 over 1 year for the no-sharing, optimal and hybrid policies in countries A and B given different epidemic coupling constants ($\kappa \in [10^{-8}, 10^{-1}]$) and three vaccination rates (50%, 75% and 100% of the population vaccinated in 1 year). The hybrid policy maintains a vaccine sharing fraction of 0.33 to the left of the vertical black line, where the optimal vaccine sharing fraction is lower than 0.33 (shown here in cyan). To the right, the optimal vaccine sharing fraction is equal or greater than 0.33, so the hybrid vaccine sharing fraction is equal to the optimal in this region (shown here in magenta). The interpretation of the curves is same for each of the panels: blue denotes fatalities in A and red denotes fatalities in B. For each, the results are shown for no-sharing (dotted), optimal sharing (solid) and hybrid (dashed).

donor country. We find that in the regime of high vaccination rates and low to moderate values of the epidemic coupling coefficient, the optimal sharing fraction is 0, supporting the results shown in [6]. However, as the vaccination rate decreases, the optimal policy is to share vaccines. We interpret this finding as follows: when vaccination rates are low and stockpiles are high, then a donor country is not effectively using its vaccine. Instead, a large number would get infected before they get an opportunity to get vaccinated. Hence, it is better for a donor country to share vaccines with a recipient country. As a result, the recipient country begins to vaccinate individuals thereby reducing the force of cross-infection due to coupling between the countries. We find that vaccine sharing becomes generic and can increase to high levels in the limit of low per-capita vaccine rates and moderate coupling (and note that vaccine sharing remains optimal even in the limit of very low coupling when vaccination rates are sufficiently low).

The finding that selfish objectives leads to altruistic sharing policies can be extended to adjacent, near-optimal policies. We propose a hybrid policy that involves sharing vaccines (e.g., 1/3 of the vaccine stock) even when the optimal policy is no-sharing. As vaccination rates decrease, then this hybrid policy has minimal impacts on fatalities in the donor country while leading to significant reductions in fatalities in the recipient country. The benefit of these suboptimal policies lie in the significant reduction in fatalities in the recipient country, where the reduction in deaths can often be more than 50%, when compared to the optimal. Thus, in certain cases, it might make sense to employ such a hybrid policy for the significant effect it can have in the recipient country, although such decisions no longer remain strictly selfish.

The model used for simulating the epidemic and for evaluating vaccine sharing policies comes with caveats. The effect of infections in one nation on another is simulated through the use of a epidemic coupling constant rather than through more complex (and time-varying) travel policies. In searching for optimal sharing policies, we assume both nation have equal vaccination rates (given available stockpiles) and efficiency of isolating infected cases. In reality, wealthy nations likely can vaccinate at a higher rate and are likely to be more efficient in case tracing and isolation than lower and middle income countries. Finally, we have assumed that immunity does not wane over the time-scale of the optimization (i.e., approximately 1 year). In reality, immunity wanes due to intrinsic changes and emergence of new variants [9, 10, 11]. Developing dynamic policies that take into account waning immunity, changes in vaccine effectiveness, and the emergence of variants represents critical next steps to extend the present framework.

In summary, the optimization framework developed here demonstrates the value of altruistic sharing of vaccines based on the selfish objective of minimizing fatalities in one's own nation. Our results show realistic regimes (based on the vaccination rate and epidemic coupling constant) where sharing vaccines result in a significant reduction in fatalities for both the donor and recipient nation. Moving forward we hope that this optimization framework encourages re-evaluation and action-taking to explore the mutual benefits of vaccine-sharing to other nations in need.

5 Methods

The disease dynamics are analyzed through an 'SEIRV' model. Instead of an isolated country, we consider two nations, both modelled via simple SEIRV dynamics. The subpopulations for country 'i' ($i \in \{A, B\}$), are susceptible S_i, exposed E_i, infectious I_i, recovered R_i , vaccinated V_i, with the total number of fatalities denoted by D_i. The total population vector of country 'i' is given by $P_i = [S_i, E_i, I_i, R_i, V_i]^T$. The dynamics of the two nations are coupled through their *force of infection*. Now, for country 'i' let c_S, c_E, c_I, c_R and c_V equal the contact rate of S_i, E_i, I_i, R_i and V_i individuals respectively (contact rates for subpopulations are assumed same across countries), with $c = [c_S, c_E, c_I, c_R, c_V]$ and η_I be the measure of disease transmission effectiveness from I class to S class [12] and κ be the epidemic coupling constant encapsulating the reduced contact rate between populations of A and B. The force of infection in country 'i' is:

$$F(P_i, P_j, \kappa_i) = \eta_I c_S \left[\frac{c_I(I_i + \kappa I_j)}{c^T(P_i + \kappa P_j)} + \kappa \frac{I_j + \kappa I_i}{c^T(P_j + \kappa P_i)} \right]. \tag{1}$$

The first term calculates with the probability of the susceptible population in 'i', S_i, coming in contact with the infected population of nation i, I_i, and the infected population of nation 'j', I_j, in nation 'i'. Since we consider the effect of a population outside its native nation (I_j and P_j), the effective contact rate is reduced by a factor equal to epidemic coupling constant. The second term measures the probability of the interaction of S_i with I_i and I_j, but in nation 'j'. Since the interaction is considered in nation 'j', the effective contact rate of S_i, I_i and P_i is reduced by the epidemic coupling constant.

Suppose all the contact rates are equal to a baseline contact rate c_B and $\kappa = 0$, i.e. the two nations are not coupled. Assuming relatively few fatalities per capita, then the total population is approximately constant at N, such that the force of infection can be approximated as $F \approx \eta_I c_B (I/N)$, which recovers the standard SEIR model by defining $\beta = \eta c_B$ as the *baseline infection rate*. Let λ be the daily vaccination rate for the S_i subpopulation, as we assume that a person can only get vaccinated if in susceptible state. λ is dependent on vaccine availability and is a constant as long as stocks last, and then reduces to 0. Let the total vaccines available before sharing be V_0. V_i^{ini} is the initial vaccine stock in country 'i', s.t. $V_A^{ini} = (1-\mu)V_0$ and $V_B^{ini} = \mu V_0$; T_{inf} is the infectious period, T_{inc} is the incubation period, and μ is the case fatality ratio for infected individuals. In the generalized case, the model for country 'i' is given by the following system of nonlinear differential equations:

$$\begin{aligned}
\dot{S}_i &= -F(P_i, P_j, \kappa) S_i - \lambda(V_i^{ini}, S_i) \\
\dot{E}_i &= F(P_i, P_j, \kappa) S_i - \frac{1}{T_{inc}} E_i \\
\dot{I}_i &= \frac{1}{T_{inc}} E_i - \frac{1}{T_{inf}} I_i \\
\dot{R}_i &= (1-\mu) \frac{1}{T_{inf}} I_i \\
\dot{V}_i &= \lambda(V_i^{ini}, S_i) \\
\dot{D}_i &= \frac{\mu}{T_{inf}} I_i.
\end{aligned} \tag{2}$$

The contact rate for all subpopulations except the infected individuals is equal to the baseline contact rate, c_B. The contact rate for infected individuals is set to $c_B/2$, to emulate infected individuals partially isolating.

At the start of the simulation, country A donates a fraction of its vaccine stock to B, termed μ. This vaccine sharing event occurs only once at the start and determines the vaccine stock available in both

Parameter	Meaning	Value
η_I	Measure of disease transmission effectiveness	0.1
T_{inc}	Mean incubation period	4 days
T_{inf}	Mean infectious period	6 days
μ	Case fatality ratio of infected cases	0.01
c_B	Baseline potentially infectious contact rate	5/day
$S_i(0)$	Initial susceptible population in country 'i'	$10^7 - 500$
$E_i(0)$	Initial exposed population in country 'i'	0
$I_i(0)$	Initial infected population in country 'i'	500
$R_i(0)$	Initial recovered population in country 'i'	0
$V_i(0)$	Initial vaccinated population in country 'i'	0
$D_i(0)$	Initial fatalities in country 'i'	0
V_0	Total vaccines available to country A	7×10^6
t_f	Time horizon	360 days

Table 2: Parameters and initial conditions used in state equations (2). In the table above, $i \in \{A, B\}$ and the initial conditions for both nations are the same.

countries which is used for inoculating their respective populations. We formulate an optimization problem over all possible values of μ with the aim of minimizing the fatalities in country A at the final time. In order to do so, we define a cost function of μ, $J(\mu) = D_A(t_f)$ (where $D_A(t)$ is the deaths in country A at time t), such that the optimization problem can be written as

$$\min_{\mu \in \Omega} J(\mu) = \min_{\mu \in \Omega} D_A(t_f), \tag{3}$$

where $\Omega = [0, 1]$. We implement a gradient descent algorithm to compute the optimal μ for optimization problem (3). In order to do so, we need to evaluate the gradient of J with respect to μ, which is done using numerical differentiation (see https://github.com/WeitzGroup/vaccine_allocation for code). All code is written in MATLAB 2021a.

The gradient descent algorithm does not guarantee the convergence to the global maxima. To prevent convergence to a local maxima, we perform 'naive sampling' before the gradient descent search. First, we divide the linear search space into intervals with a desired resolution ϵ (here $\epsilon = 0.03$) and find the cost function's value at the center of each interval. Then, we select the center-point which gives the smallest value for J and choose that as the starting point of the gradient descent algorithm. If the grids are small enough, this naive sampling approach will be equivalent to a 'brute-force search' of the complete parameter space. This process is iterated until the norm of the gradient is lower than the preset termination value. Once the optimal parameters are reached, they can be used to obtain the optimal vaccine sharing fraction.

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Appendix

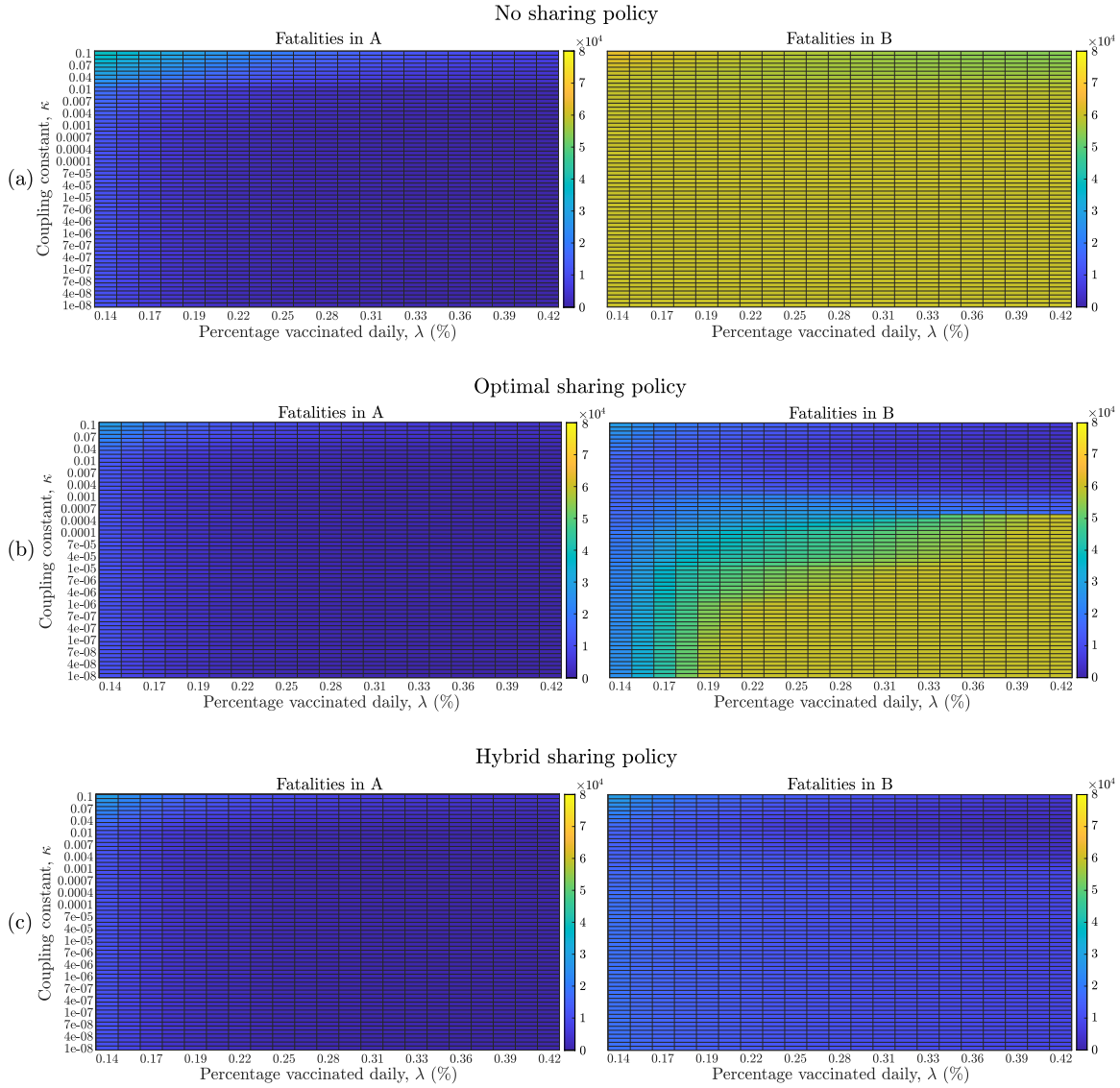

Figure S1: Fatalities in countries A and B when the **(a)** no-sharing policy, **(b)** optimal policy and **(c)** hybrid policy is implemented, over different coupling constants, $\kappa \in [10^{-8}, 10^{-1}]$ and vaccination rates, λ (from 0.14% to 0.42% of the population daily). The optimal policy has the objective of minimizing fatalities in country A and the optimal sharing fraction is μ^*. The hybrid policy is a near optimal policy with a sharing fraction of $1/3$ when $\mu^* \leq 1/3$ and equal to the optimal sharing fraction otherwise. The optimal policy shows significant reduction in fatalities in B when vaccination rate is low and coupling constant is high, when compared to the no-sharing policy. The hybrid policy results in major reduction in fatalities in B for all vaccination rates and coupling constants, when compared to the no-sharing policy. There is a slight increase in fatalities in A for the hybrid policy when the coupling constant is very small and the vaccination rate is high.

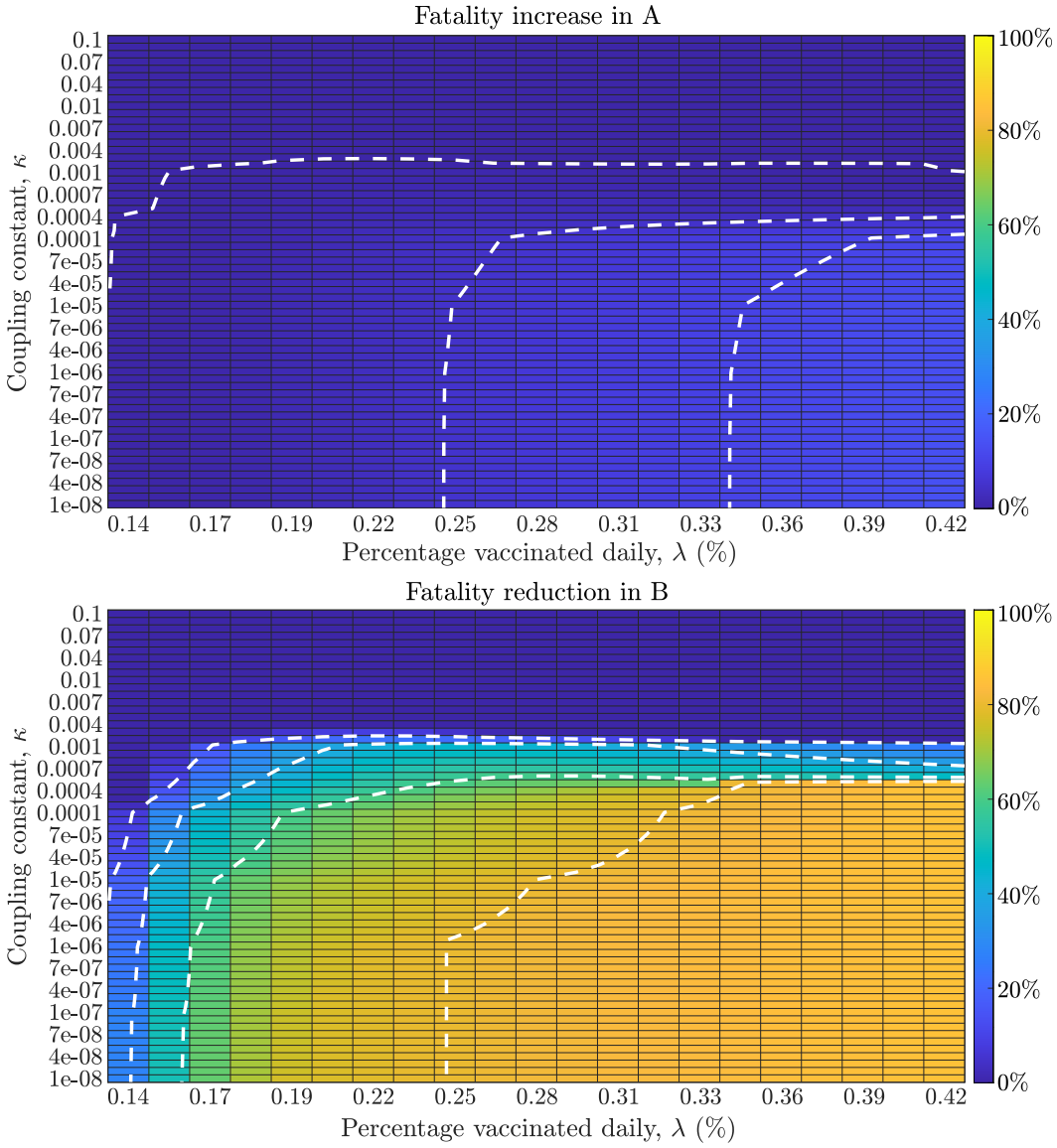

Figure S2: Percentage change in fatalities in countries A and B when comparing the hybrid policy with the optimal policy, over different coupling constants, $\kappa \in [10^{-8}, 10^{-1}]$ and vaccination rates, λ (from 0.14% to 0.42% of the population vaccinated daily). The hybrid policy is a near optimal policy with a sharing fraction of $1/3$ when $\mu^* \leq 1/3$ and equal to the optimal sharing fraction otherwise. For country A, an increase in fatalities in the range of $[0\%, 14\%]$ is observed and contours are made for 0%, 5% and 10% increase in fatalities. For country B, a decrease of fatalities in the range of $[0\%, 80\%]$ can be seen, with contours plotted for 20%, 40%, 60% and 80% fatality reduction. By relaxing the strict condition of minimizing fatalities in A, the near optimal solution provided by the hybrid policy shows significant fatality reduction in B when compared to the optimal policy. However, this comes at the cost of a small increase in fatalities in A in the regime of low coupling constant and high vaccination rate.