Efficient Epidemics: Contagion, Control, and Cooperation in a Global Game*

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Abstract

We study disease control in a global game. While disease control games of perfect information have multiple equilibria, we show that even a vanishing amount of uncertainty forces selection of a unique equilibrium, leading to several new results. In well-identified cases, an epidemic will occur albeit it is inefficient and could be avoided. More harmful diseases are less likely to become an epidemic and pose a lower burden on society. We also study cooperation and let some players commit to control the disease whenever the expected benefit is sufficiently high. Cooperation facilitates selection of an efficient equilibrium.

Keywords: global games, epidemics, disease control, privately provided public goods

JEL Codes: I18, H41, C72

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1 Introduction

Epidemics are the product of human behavior. In this paper, we study the strategic considerations governing epidemics. Our game of imperfect information is distinct from existing studies in economics that either do not study strategic behavior explicitly (Kremer, 1996; Geoffard and Philipson, 1997; Gersovitz and Hammer, 2003), or assume perfect information (Barrett, 2003; Chen, 2012). We derive several new and important insights.

Game theory provides a powerful toolkit to study the strategic nature of disease control problems, where any private agent's optimal behavior critically depends on what other agents are doing. Unfortunately, extant game theoretic analyses of disease control tend to have multiple Nash equilibria (Barrett, 2003; Chen, 2012), dwindling the predictive ability of these models. As the outcome of a game with multiple equilibria is not, a priori, determined, there is no apparent connection between a disease's fundamental properties and individual behavior aimed at controlling the disease. This conclusion is intuitively unsatisfactory, as one would expect behavioral choices to depend – among other things – on such fundamentals.

Multiple Nash equilibria may coexist when there is a positive feedback loop in individual behavior – that is, when players' actions are strategic complements (Kremer, 1996; Barrett, 2003; Chen, 2012). Such a feedback loop can result from the natural dynamic of infections. A disease spreads when infected individuals infect others. Any individual's private efforts at controlling a disease boost the likelihood that others' private efforts are successful. If this effect is strong, individual best-responses will be to mimic what the majority is doing – that is, the cost or discomfort incurred when trying to control a disease will outweigh the low probability of success when others are not taking similar actions, making it a best-response to be lax as well. Thus, when a player (be it an individual, a municipality, or even a country) is pessimistic about others' precautionary measures, the player will prefer not to take precautions itself; this makes precaution less attractive to other players and, reasoning along, we find a Nash equilibrium in which no player tries to control the disease. But the argument goes both ways. When a player expects other players to engage in precautionary behavior, the player will want to take precautions itself; this in turn induces others to indeed take precautions and we obtain a Nash equilibrium in which everyone tries to control the disease. In this sense, beliefs about other players' strategies play a crucial role and epidemics can be self-fulfilling prophecies.

While our model maintains the positive feedback loop in individual behavior, we study disease control under payoff uncertainty in a global game (Carlsson and van Damme, 1993). Global games are a class of imperfect information games where players are uncertain about some underlying fundamental of the game but receive private noisy signals of it. In our model, players are uncertain about the (net) expected benefit of controlling the spread of a disease.

There are good reasons to consider benefit uncertainty. Epidemics have a highly multi-dimensional impact on society, making a comprehensive idea of their costs hard to grasp (Case et al., 2005; Karlsson et al., 2014; Cervellati et al., 2017; Aassve et al., 2021). Moreover, the epidemiological literature suggests that new diseases – by their nature subject to many uncertainties – will appear increasingly often in the near future (see Rappuoli, 2004, for a comprehensive review). These observations motivate our analysis of disease control under uncertainty.

Even a vanishing amount of uncertainty catalyzes equilibrium selection. While equilibrium selection is well-established for global games generally, see especially Frankel et al. (2003), it is a novel insight for the economic literature on epidemics. The key advantage of a unique (Bayesian) Nash equilibrium is that it allows for sharp predictions. In equilibrium, a more harmful disease is more likely to be controlled and thus impairs fewer people. In terms of welfare, an epidemic can occur even though it is inefficient and could have been avoided. These results embed well-known predictions from epidemiology (*c.f.* Capasso and Serio (1978)) within a strategic framework and are supported empirically (Ahituv et al., 1996).

After proving equilibrium uniqueness and deriving its implications, we consider a simple extension of the game. For reasons exogenous to the model, prior to the outbreak of a disease some subset of players forms a coalition. Membership to the coalition entails a credible pledge to take disease control measures whenever the expected benefit of control is above some exogenous threshold. We show that such a pledge helps selecting a more favorable equilibrium, decreasing the likelihood of an epidemic. One way to interpret this result is to say that ex ante cooperation among players facilitates coordination when the need arises.

Our model yields additional insights on how societies can prepare for future disease outbreaks. Lowering the number of players in the game (for example, by planning disease control efforts at a more aggregated level) or lowering the costs of disease control help to avoid future epidemics. Though intuitively plausible, extant game theoretic analysis of disease control do not yield these implications (at the margin). Our model is the first to embed intuitive policy solutions within a formal strategic framework.

The analysis is sufficiently general to allow for varying interpretations, ranging from community-level epidemics to full-fledged pandemics. If we think of players as citizens, the measures implemented to control the spread of a disease may consist of social distancing. If we think of players as countries, they can include a lockdown or border closures. Whichever of these interpretations is most suitable will depend on the specificities of the disease considered. Some diseases very easily spread globally (COVID-19 or the Spanish flu). Others will be more geographically restricted, for example because their transmission relies on specific vectors (malaria), or because the disease spreads through poor sanitary conditions only present in certain regions (cholera).

The remainder of this paper is organized as follows. Section 2 presents the building blocks of our model and the main results. Section 3 incorporates cooperation into the model. Section 4 concludes. We present all the proofs in the appendix and provide intuition for our results along the text.

2 The Model

Let there be N players, indexed i and acting simultaneously. Following Barrett (2003), player i can either exert effort to control the spread of the disease ($x_i = 1$), or not ($x_i = 0$). Throughout the paper, we will use the term "effort", though it is understood that this is an umbrella term describing any attempt toward disease containment.[1] We write C for the cost of effort.

Conditional on n players exerting effort, let the probability that these efforts are successful be $p(n)$, where p is strictly increasing in n. We normalize $p(0) = 0$ and $p(N) = 1$. Note than $p(n+1) > p(n)$ and $p(n) < 1$ for all $n < N$, meaning that successful control becomes more likely as more players exert effort yet is not guaranteed unless all players do. This formalizes the idea that diseases spread when infected individuals infect others, or, on a larger scale, that a disease may spread to one country via another. One can interpret $1 - p(n)$ as the (conditional) probability of an epidemic.

[1] We focus on disease control, not eradication. Controlling a disease means reducing the number of new infections, the number of people currently infected, and the number of people who become sick or die from a disease in local settings. This is achieved through deliberate efforts including vaccinations, medications, contact isolation, or other public health interventions. Disease eradication, in contrast, is the permanent reduction of a disease to zero cases through deliberate measures such as vaccines. Once a disease has been eradicated, control measures are no longer needed. To date, the only disease considered to be globally eradicated is smallpox, illustrating the importance of studying disease control.

A player's benefit from successful control of the disease is B, drawn uniformly from $[\underline{B}, \overline{B}]$. We assume $\underline{B} < B_0 < B_1 < \overline{B}$, where $B_0 = C/p(N) = C$ and $B_1 = C/p(1)$ demarcate strict dominance regions. If $B < B_0$, the disease is harmless and it never pays to exert efforts towards controlling it, in view of the costs involved, e.g. childhood chickenpox (McKendrick, 1995). More dramatically, if $B > B_1$, the disease is so severe that a player will always want to control it, such as smallpox (Fenner et al., 1988). Finally, when $B \in (B_0, B_1)$, players play a coordination game – individual best-responses are mutually dependent and any player will want to exert effort if and only if sufficiently many others do. Figure 1 illustrates the a priori support of B.

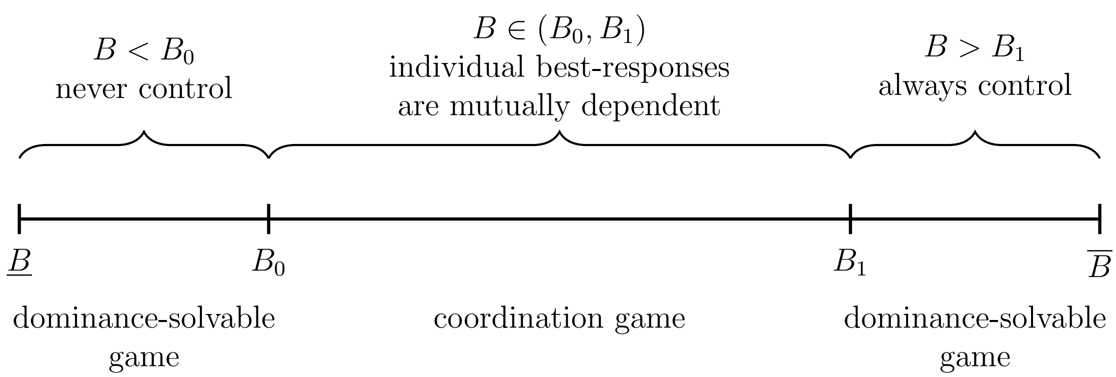

Figure 1: Support of benefit parameter B.

Given n players $j \neq i$ play $x_j = 1$, the payoff to player i is:

$$u_i(x_i; B, n) = [p(n + x_i) \cdot B - C] \cdot x_i, \quad (1)$$

where $p(n + x_i) \cdot B$ is the expected benefit from controlling the spread of the disease. We normalize payoffs relative to no effort ($x_i = 0$), so player i exerts effort if and only if the expected payoff thereof is positive: $u_i(x_i = 1; B, n) \geq 0$. Since the probability of success p is increasing, the expected payoff to exerting effort is increasing in the number of other players exerting effort. This positive feedback loop is driven by strategic complementarity in game theoretic parlance.

The source of strategic complementarity will vary with the interpretation of our model. Perhaps the most intuitive case arises when players are countries. The success of a single country's measures to halt a pandemic depend crucially on whether or not similar policies are pursued abroad, especially in a globalized world where diseases spread rapidly due to such factors as urbanization (Alirol et al., 2011) and international mobility (Tatem et al., 2006).[2] Disease prevention may also exhibit strategic complementarities at less grand scales (Chen, 2012). Consider a household in a land plagued by an infectious disease. If one person in the household continues to go out and live a life as though nothing were going on, then the others have hardly any incentive to try and prevent getting infected – after all, infections are almost sure to spread within the household anyway. Similarly, Kremer (1996) studies a model of the HIV epidemic where increases in disease prevalence create a positive feedback via behavioral adaptations. Empirical evidence confirms our hypothesis of positive feedback effects for a wide range of health phenomena including the choice to get vaccinated (Bouckaert et al., 2020), risky behaviors (Ruhm, 2019), and blood donations (Bruhin et al., 2020).

Another way to think about strategic complementarities is in terms of timing. An interpretation consistent with (1) assumes that a disease has already permeated society so that, even when all other players take efforts towards controlling the disease, an individual player will anyway suffer the disease's negative consequences if it does not take such efforts itself; that is, after being infected one cannot free ride on the efforts taken by other players.[3] For example, Portugal's national policies to control a disease will not, generally, halt this disease in The Netherlands as well, assuming the latter has already experienced cases.

[2] The re-introduction of smallpox in Botswana from South-Africa serves as a poignant example of this mechanism (Fenner et al., 1988).

[3] Importantly, our normalization of (1) does not impose that player i's payoff to free-riding (playing $x_i = 0$) be constant in the number n of players exerting effort (playing $x_j = 1$). It is allowed that free-riding becomes more beneficial as n goes up. All we require is that the expected benefit of exerting effort increases *more*.

Proposition 1 (Perfect information: multiple equilibria)**.** *In the game of perfect information, for all* $B \in (B_0, B_1)$*, there are two pure strategy Nash equilibria, one in which* $x_i = 1$ *for all* i*, another in which* $x_i = 0$ *for all* i*. The equilibrium in which the epidemic is not controlled is inefficient when* $B \in (B_0, B_1)$*.*

Proposition 1 establishes equilibrium multiplicity in the game of perfect information. With multiple equilibria, no posterior on the probability of an epidemic is rationally favored over another. As a consequence, one cannot predict other players' behavior on the basis of a disease's fundamentals like the benefit of control B. Meanwhile, beliefs about what others will do – beliefs about n – play a crucial role in determining a player's best-response. If a player is pessimistic about others' efforts toward control, then it is rational for the player itself not to exert effort (Auld, 2003). Since this is true for all players, epidemics can be self-fulfilling prophecies.

While Proposition 1 is theoretically sound, intuition suggests – and the empirical evidence confirms – that factors such as the cost and (expected) benefit of exerting effort towards controlling a disease should affect individual behavior and therefore the equilibrium of the game. In this sense, the model of perfect information offers an unsatisfactory economic and behavioral theory of epidemics. As a (perhaps paradoxical) solution, we suggest to add the realistic assumption that players are uncertain about the benefit of control.

2.1 Global Game

In the global game, the benefit B is unobserved. It is common knowledge that B is drawn from the uniform distribution on $[\underline{B}, \overline{B}]$ and that each player i receives a private noisy signal b_i of B, given by:

$$b_i = B + \varepsilon_i.$$

Here, ε_i is the noise in player i's signal, a random variable drawn i.i.d. from the uniform distribution on $[-\varepsilon, \varepsilon]$, with $\varepsilon > 0$ a measure of the uncertainties surrounding the disease. By construction, players' private signals are correlated as all have the same mean; however, conditional on this mean, signals are independent.

In the global game, individual policies are chosen to maximize expected payoffs:

$$u_i^e(x_i; b_i, n) = \frac{1}{2\varepsilon} \int_{b_i-\varepsilon}^{b_i+\varepsilon} [p(n + x_i) \cdot B - C] \cdot x_i \, dB, \tag{2}$$

which, ceteris paribus, is increasing in b_i. Observe that equation (2) gives almost exactly equation (1) if ε becomes small.

We solve the global game by iterated elimination of strictly dominated strategies. For iterated dominance to work, there should exist signals which support any of the two actions (effort and no effort) as a strictly dominant strategy. We therefore assume:

$$0 < 2\varepsilon < \min\{B_0 - \underline{B}, \overline{B} - B_1\}. \tag{3}$$

We are now ready to state Theorem 1, our first substantive result. It states that uncertainty about the benefit B leads to selection of a unique equilibrium. The equilibrium strategy is increasing: a player will try to control a disease only if the benefit is sufficiently large. It does not pay to eliminate a fairly harmless disease. The contrast with the game of perfect information and Proposition 1 is stark.

Theorem 1 (Unique equilibrium)**.** *Given C, for any $B \in [\underline{B}, \overline{B}]$, the game has a unique Bayesian Nash equilibrium. For all $i \in \{1, 2, ..., N\}$, let x_i^* denote the associated equilibrium strategy. Then there exists a unique $b^* \in (B_0, B_1)$ such that, for all $i \in$*

$\{1, 2, ..., N\}$:

$$x_i^*(b_i) = \begin{cases} 1 & \textit{if} \quad b_i \geq b^* \\ 0 & \textit{if} \quad b_i < b^* \end{cases}. \tag{4}$$

A qualitatively similar result obtains if players are heterogeneous, say due to differences in their costs of control or their individual contribution to the probability of successful control for other players. This is an immediate consequence of the general results in Frankel et al. (2003). We focus on the case of homogeneous players for simplicity of the exposition.

For the intuition behind Theorem 1, recall that any $B \in (B_0, B_1)$ supports two Nash equilibria in the game of complete information, making it impossible for players to guess each other's actions. When B is not known and players receive a private noisy signal of it, a player knows neither the precise value of B nor the signal received by any other player. However, player i *does* know that the signal b_j (for $j \neq i$) must be drawn from $(b_i - 2\varepsilon, b_i + 2\varepsilon)$. For a high (low) enough b_i, player i therefore knows that the signal received by j includes a region for which $x_j = 1$ ($x_j = 0$) as a strictly dominant strategy. Players in the global game are hence forced to construct upper or lower bounds on the probability that any other player will (not) exert effort, which is not the case in a complete information game. Thus, knowing that any other player will exert effort toward control for high signals ($b_j > B_1$ when $\varepsilon \to 0$), each player i will want to take effort toward control even for some signals just below B_1 since, for these signals, the estimated minimum probability that any other player received a signal above B_1 and therefore will exert effort is close to 50% – quite different from the strongly pessimistic assumptions on other players' behavior required to support a no-effort equilibrium in the game of complete information! Since this argument applies to every player, we can find a new threshold $B_1^1 < B_1$ such that, assuming no player plays a strictly dominated strategy, every player is best off exerting effort toward control for all signals above B_1^1. There is no reason to stop now; a rational player will repeat the argument. Thus, knowing that any player will exert effort toward control for all signals above B_1, any player will in fact exert effort for all signals above the lower threshold B_1^1; and since all know this, all can also find yet a new threshold $B_1^2 < B_1^1 < B_1$ such that each player prefers to exert effort for all signals above B_1^2, and so on. Proceeding in this way allows players to expand the range of signals for which (not) exerting effort is a strictly dominant strategy and eventually converges to a point B_1^∞ (B_0^∞) as shown in Figure 2.

As a final step, note that B_1^∞ and B_0^∞ have to be the same point. By definition of B_0^∞, player i prefers to exert effort if he receives a signal greater or equal to B_0^∞. But, by definition of B_1^∞, player i prefers not to exert effort if he receives a signal smaller or equal to B_1^∞. Thus, if B_0^∞ and B_1^∞ are not the same, it must be that player i is simultaneously better off and worse off by exerting effort when he receives a signal between B_0^∞ and B_1^∞, a contradiction. We write $B_1^\infty = B_0^\infty = b^*$.

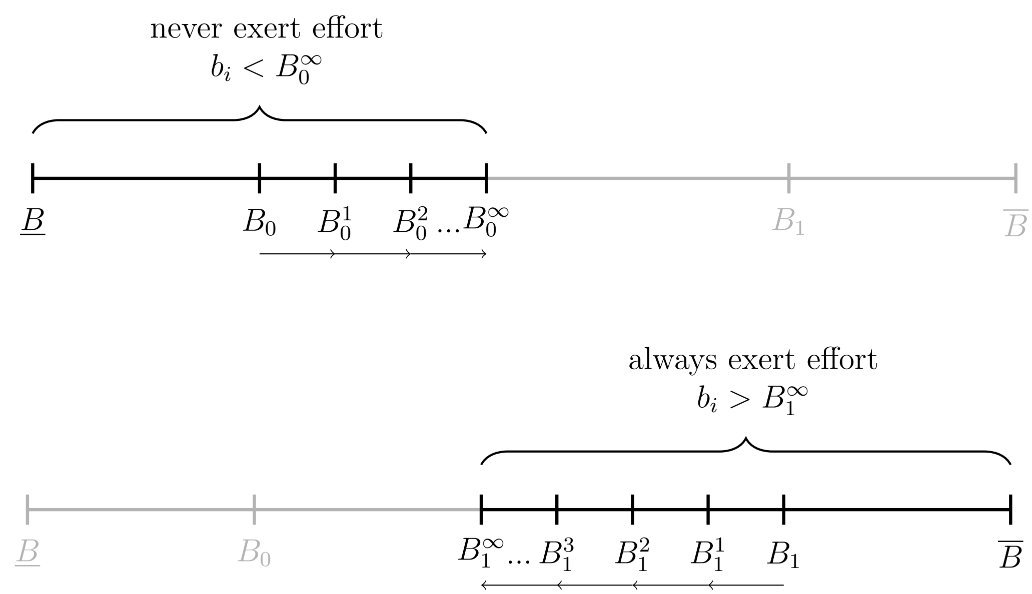

Figure 2: Iterated dominance illustrated.

If player i observes signal $b_i = b^*$, then i's posterior distribution on the signal b_j received by any player $j \neq i$ is symmetric around b^*. Moreover, from Theorem 1 we know that any player j will exert effort if and only if $b_j > b^*$ so that, when i receives $b_i = b^*$, its posterior on j's action is fifty-fifty. These observations allow us to characterize b^*.

Proposition 2 (Characterization)**.** *Let $\varepsilon \to 0$. The threshold b^* is given by:*

$$b^* = \frac{2^{N-1}}{\sum_{k=0}^{N-1} \binom{N-1}{k} p(k+1)} \cdot C. \tag{5}$$

Given the characterization of the equilibrium threshold b^*, we can investigate the effect of certain structural properties of our model on equilibrium behavior.

Proposition 3 (Comparative statics)**.**

(i) The threshold b^* is monotone increasing in C;

(ii) The distance between B_0 and b^* is strictly increasing in C;

(iii) The threshold b^* is decreasing in first-order stochastically dominating probability-of-successful-control functions p.

It is intuitive that b^* is unambiguously increasing in the cost of effort. When costs are higher, a player is exposed to greater risk when exerting effort. To compensate, the expected benefit should go up as well. In terms of policy implications, this implies that the probability of an epidemic can be decreased by lowering the cost of effort. Similarly, looking at (5), the threshold for taking effort is *increasing* in N, the number of players. Hence, if the game is played by fewer actors, the probability that an epidemic is avoided increases. For policy, this suggests that more aggregated decision making may help preventing epidemics. Finally, observe that a stochastically dominating probability-of-success function p may be interpreted as stricter social distancing or border closures as both tend to decrease the probability that one individual infects another. Intuitively, our model suggests that strong social distancing avoids epidemics – directly because social distancing reduces the number of secondary infections for any infected person, but also indirectly through its effect on equilibrium behavior! While all of these predictions seem intuitive, they are not supported by games with multiple equilibria, which strengthens the case for our global games approach.

In the special case that p is linear (i.e. $p(n) = n/N$), the characterization of b^* simplifies to:

$$b^* = \frac{2N}{N+1} \cdot C, \tag{6}$$

which is increasing in N, the number of players. In the extreme case of a continuum of players we see that $b^* = 2C$, whereas the minimum "markup" of benefits over costs is 33% (plug in $N = 2$). Hence, for any number of players N the cutoff signal at which a player is going to exert effort toward control is strictly higher than the cost of control. This suggests that the equilibrium may be inefficient. The following proposition elaborates.

Proposition 4 (Inefficiency)**.** *For all $B \in (B_0, b^*)$, an epidemic is inefficient. Moreover:*

(i) For all $B < b^* - \varepsilon$, the epidemic will not be controlled. For all $B > b^* + \varepsilon$, the epidemic will be controlled;

(ii) For all $B \in (b^* - \varepsilon, b^* + \varepsilon)$, the probability than an epidemic is controlled is monotone decreasing in B.

(iii) The ex ante probability of an inefficient epidemic is strictly increasing in C and strictly decreasing in $p(n)$, for any n.

Proposition 4 says that a disease is more likely to be controlled if the benefit of successful control is higher. Though intuitive, such a result is not true in a game of perfect information (Proposition 1), once again motivating our global games approach to the study of epidemics. Relatedly, the proposition tells us that an inefficient epidemic will occur only for relatively low B.[4]

Proposition 5 (Speed bump effect)**.** *In equilibrium, a disease for which the benefit of containment is high ($B > b^* + \varepsilon$) imposes lower social costs than a disease for which the benefit of containment is low ($B < b^* - \varepsilon$).*

In equilibrium, more harmful diseases pose a lower burden on society because a sufficiently harmful disease, for which $B > b^* + \varepsilon$, will be controlled whereas a milder disease, for which $B < b^* - \varepsilon$, will not. Although this effect is recognized in the epidemiological literature (Capasso and Serio, 1978), to our knowledge it is a novel insight in the economic literature on epidemics.

Finally, we briefly return to the payoff function (1). Although we argue that there are good reasons to assume strategic complementarities in effort, these are not important drivers of our results. Harrison and Jara-Moroni (2020) show that global games with strategic *substitutes* and sufficiently precise signals also have a unique equilibrium (if players are heterogeneous). Similar to Theorem 1, this equilibrium will be in increasing strategies. Their result indicates that our predictions are not specific to our assumption of strategic complementarities. They appear to be fundamental properties of modeling disease control as a global game.

3 Committed Coalitions

Proposition 4 in the previous section shows that the decentralized equilibrium outcome may be inefficient. An important question is therefore how one can manipulate the

[4]By the way, note that the only source of inefficiency, in equilibrium, is that an epidemic occurs even though the benefits from disease control outweigh the costs. It is never possible, in equilibrium, that an epidemic is avoided even though society would be better off having one.

game in order to get closer to, or reach, an efficient equilibrium. One way of achieving this could be the provision of public information about B (Angeletos and Pavan, 2007). We propose another option: ex ante cooperation.

For reasons exogenous to the model, prior to the outbreak of a disease let $\bar{n} \leq N$ players form a coalition. Each player i in the coalition credibly commits to exerting efforts whenever a disease arises for which control is perceived to be of some minimum benefit $b^c \in [B_0, b^*]$. That is, each i in the coalition commits to playing strategy $x_i^*(b_i) = 1$ for all $b_i \geq b^c$. Precisely what constitutes a credible commitment lies beyond the scope of our analysis. Rather, the question of interest is how, *given* such commitments are made, the equilibrium and its properties will be affected. Without loss of generality, reshuffle the set of players so that the coalition consists of all players $i \in \{1, 2, ..., \bar{n}\}$. Players still act simultaneous. To our knowledge, we are the first to study this type of commitment in a global game.

Theorem 2 (Equilibrium with a coalition)**.** *Given $\bar{n}$, the game has a unique Bayesian Nash equilibrium. For all $i \in \{\bar{n}+1, ..., N\} \supseteq \{N\}$, let $x_i^*(\cdot; \bar{n})$ denote the associated equilibrium strategy. Then, conditional on $\bar{n}$, there exists a unique $b^*(\bar{n})$ such that, for all $i \in \{\bar{n}+1, ..., N\}$:*

$$x_i^*(b_i) = \begin{cases} 1 & \text{if} \quad b_i \geq b^*(\bar{n}) \\ 0 & \text{if} \quad b_i < b^*(\bar{n}) \end{cases}. \tag{7}$$

Moreover, $b^*(\bar{n})$ is monotone decreasing in $\bar{n}$, with $b^*(0) = b^*$ and $b^*(N) = b^c$.

While the unique equilibrium is passed on from the static to the coalition game, its properties are somewhat different.

Proposition 6 (Inefficiency with a coalition)**.** *For all $B \in (B_0, b^*(\bar{n}))$, an epidemic is inefficient. Moreover,* *(i) The probability of an inefficient epidemic is decreasing in $\bar{n}$, the number of players in the coalition;*

(ii) The probability of an epidemic is monotone decreasing in the (true) benefit B.

Theorem 2 and Proposition 6 qualify a call for strong ex ante cooperation. If players can commit to try and control diseases for which the benefit thereof is sufficiently high, the results show that inefficient epidemics are more likely to be avoided.

4 Conclusion

This paper studies disease control in a global game. Our approach stands in contrast to the existing game theoretic literature. While disease control games of perfect information have multiple equilibria, our global game has a unique equilibrium. This primal distinction leads to several derivative, yet important, results. First, our model can predict when an (in)efficient epidemic occurs. Second, diseases for which the benefit of successful control is higher are more likely to be controlled. Third, diseases that are more costly a priori end up being less costly to society, precisely because these get contained. Our analysis is the first to embed these well-known predictions from epidemiology models within a strategic framework.

Our results clearly demonstrate that an epidemic may occur even when this is inefficient. One way to avoid this dismal outcome is to lower the costs of disease control. Another possibility is to reduce the set of players, for example by having countries coordinate policies through more aggregated bodies such as the European or African Unions. Third, strong social distancing or hard border closures can contribute to contain a disease. While intuitive, extant game theoretic models do not support these conclusions.

An alternative solution is strong ex ante cooperation between players. We support this claim in an extension of our static game, in which a subset of players forms a coalition prior to the outbreak of a disease. Members of the coalition credibly commit to exert efforts towards disease control whenever the benefit is perceived to be sufficiently high. We show that credible commitment catalyzes coordination on disease control efforts and decreases the likelihood of inefficient epidemics.

There are at least two ways to think about a coalition. First, as the outcome of intensive ex ante cooperation among players. This is perhaps most intuitively thought of as international cooperation between countries through a supra-national entity such as the World Health Organization. Second, as a reduced-form description of a sequential global game, where a subset of players determines its actions first, and only then do the remaining choose theirs.

This paper offers a new perspective on the economics of disease control. Existing studies either do focus on strategic considerations (Kremer, 1996; Geoffard and Philipson, 1997; Gersovitz and Hammer, 2003), or make the strong assumption of perfect information (Barrett, 2003; Chen, 2012). Our global game incorporates the strategic incentives underlying the spreading of a disease while taking explicit account of uncertainty. Our results provide useful insights on how societies can prepare for future disease outbreaks, highlighting the need for increased cooperation to avoid future epidemics.

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Appendix

Proof of Theorem 1

Denote $n = \sum_{j \neq i} x_j$. Let $F_i(B; b_i)$ denote i's posterior density of B, given its signal b_i. Let $G_i(n; B, \beta)$ denote the density of n, conditional on B *and* assuming all players $j \neq i$ play strategy $x_j(b_j) = 0$ for all $b_j < \beta$ and $x_j(b_j) = 1$ for all $b_j \geq \beta$. For given B, the density $F_i(B; b_i)$ is continuously (weakly) decreasing in b_i. Moreover, for given B, $G_i(n; B, \beta)$ is continuously (weakly) increasing in β, and given β, $G_i(n; B, \beta)$ is continuously (weakly) decreasing in B.

Given the "strategy" summarized by β, player i's rationally expected payoff is given by $\iint u_i(x_i; B, n)\, dG(n; B, \beta)\, dF(B; b_i)$, which is strictly and continuously increasing in b_i and n.

Having set the stage, we proceed with the proof in three steps and each step corresponds to a lemma in the proof. The first step starts at $b_i = B_0$ and uses iterated elimination of strictly dominated strategies to find the signal that makes player i indifferent between controlling the spread of the disease or not; The second step does the analogous exercise starting from $b_i = B_1$; The third and last step shows that the signals found in the previous steps are the same.

Proof. Since the payoff to exerting effort toward controlling the disease is increasing in n, the *maximum expected payoff* to exerting effort for player i is obtained by assuming all players $j \neq i$ exert effort unless doing so is a dominated strategy. Because $x_j(b_j) = 0$ is dominant for all $b_j < B_0$, the initial density of the maximum global disease control efforts is therefore $G(n; B, B_0)$.

Lemma 1 (Maximum payoff)**.** *There exists a unique $\bar{b}$ such that the maximum expected payoff to exerting effort is 0 iff $b_i = \bar{b}$, for all i, where $\bar{b}$ solves: $\iint u_i(x_i; B, n)\, dG(n; B, \bar{b})\, dF(B; \bar{b}) = 0$.*

Proof. Start at $b_i = B_0$. It is immediate that $\iint u_i(x_i; B, n)\, dG(n; B, B_0)\, dF(B; b_i = B_1) > \int u_i(x_i; B, n = 0)\, dF(B; b_i = B_1) = 0$, where the equality follows from the fact that B_1 demarcates the strict dominance of $x_1 = 1$ (and the fact that noise is distributed uniformly). Define B_1^1 as the point that solves: $\iint u_i(x_i; B, n)\, dG(n; B, B_0)\, dF(B; b_i = B_0^1) = 0$. That is, assuming no j plays a dominated strategy, then i's minimum payoff to playing $x_i(b_i)$ is positive for all $b_i < B_0^1$. Since this is true for all players, all $i \in \{1, 2, ..., N\}$ will play $x_i(b_i) = 0$ for all $b_i < B_0^1$. Hence, knowing this, the maximum expected payoff to exerting effort for i is obtained by assuming that all players j for whom $b_j \geq B_0^1$ play $x_j(b_j) = 1$.

Proceeding this way, for all $k \geq 1$ let us inductively define $\iint u_i(x_i; B, n)\, dG(n; B, B_0^k)\, dF(B; b_i = B_0^{k+1}) = 0$. We thus obtain a sequence $(B_0, B_0^1, B_0^2, ...)$, where $B_0 < B_0^k < B_0^{k+1}$ for all $k > 0$. A monotone sequence defined on a closed real interval converges to a point in the interval, which we call $\bar{b}$. Since $\bar{b}$ is the limit of our sequence $(B_0, B_0^1, B_0^2, ...)$, it by definition solves $\iint u_i(x_i; B, n)\, dG(n; B, \bar{b})\, dF(B; \bar{b}) = 0$. ■

The *minimum expected payoff* to exerting disease control effort is obtained by assuming no player $j \neq i$ will exert effort unless it is a dominant strategy. Since $x_j(b_j) = 1$ is dominant for all $b_j \geq B_1$, the initial distribution of n consistent with the minimum expected payoff to exerting effort is given by $G(n; B, B_1)$.

Lemma 2 (Minimum payoff)**.** *There exists a unique $\underline{b}$ such that the minimum expected payoff to exerting effort is 0 iff $b_i = \underline{b}$, for all i, which solves: $\iint u_i(x_i; B, n)\, dG(n; B, \underline{b})\, dF(B; \underline{b}) = 0$.*

Proof. Start from $b_i = B_1$. The proof then follows the structure in Lemma 1, but assumes minimum (rather than maximum) rational disease control efforts. That is, we define B_0^1 as the solution to $\iint u_i(x_i; B, n)\, dG(n; B, B_1)\, dF(B; b_i = B_1^1) = 0$. Thereafter, for all $k \geq 1$, we inductively define B^{k+1} to solve $\iint u_i(x_i; B, n)\, dG(n; B, B_0^k)\, dF(B; b_i = B_0^{k+1}) = 0$. We thus obtain a sequence $(B_1, B_1^1, B_1^2, ...)$, where $B_1 > B_1^k > B_1^{k+1}$ for all $k > 0$. A monotone sequence on a closed real interval converges to a point in the interval. We call this point $\underline{b}$. Being the limit of the inductively defined sequence, it is the unique solution to $\iint u_i(x_i; B, n)\, dG(n; B, \underline{b})\, dF(B; \underline{b}) = 0$. ■

Lemma 3. $\bar{b} = \underline{b}$.

Proof. By definition:

$$\iint u_i(x_i; B, n)\, dG(n; B, \bar{b})\, dF(B; \bar{b}) = 0 = \iint u_i(x_i; B, n)\, dG(n; B, \underline{b})\, dF(B; \underline{b}),$$

■

so $\underline{b} = \bar{b}$. We label $b^* = \underline{b} = \bar{b}$. Since even the minimum payoff to exerting effort is positive for all $b_i \geq b^*$, any rational strategy x_i^* must satisfy $x_i^*(b_i) = 1 \iff b_i \geq b^*$. Moreover, since even the maximum gain to exerting effort is negative for all $b_i < b^*$, any rational strategy must satisfy $x_i^*(b_i) = 0 \iff b_i < b^*$. ■

Proof of Proposition 2

Proof.

1. If i receives $b_i = b^*$, its posterior is that $b_j > b^*$ (and $b_j < b^*$) with probability 1/2 (and 1/2), for all $j \neq i$. Hence, i thinks that $x_j = 0$ or $x_j = 1$ each with probability 1/2.

2. There are a total of N players, so there are $N - 1$ players who are not player i. By the previous point, the probability of any vector $(x_j)_{j \neq i}$ is therefore $(1/2)^{N-1}$.

3. If there are $N - 1$ other players, the number of different vectors $(x_j)_{j \neq i}$ that contain exactly k ones and $N - 1 - k$ zeroes is $\binom{N-1}{k}$.

4. Hence, the total probability that $\sum_{j \neq i} x_j = k$ is simply the probability of any vector times the number of possible vectors that contain precisely k zeroes: $(1/2)^{N-1} \cdot \binom{N-1}{k}$.

5. Given k players $j \neq i$ play $x_i = 1$, the expected benefit to player i (from playing $x_i = 1$), who has observed signal b^*, is $p(k + 1) \cdot b^*$.

6. The expected payoff to player i from playing $x_i = 1$, given $b_i = b^*$, is therefore: $b^* \sum_{k=0}^{N-1} \frac{1}{2}^{N-1} \binom{N-1}{k} p(k + 1) - C$.

7. Solving for the b^* that makes this expected payoff equal to zero, we obtain the proposition.

The boundaries in (**??**) follow directly from evaluating (5) at $p(n) = 0 \;\forall\; n < N$ and $p(n) = 1 \;\forall\; n > 1$, respectively. In the linear-p case, equation (5) reduces to:

$$b^* = \frac{2^{N-1} \cdot N}{\sum\limits_{k=0}^{N-1} \binom{N-1}{k}(k + 1)} \cdot C.$$

The denominator of this expression can be rewritten as $\sum_{k=0}^{N-1}\binom{N-1}{k}(k+1) = \sum_{k=0}^{N-1}\binom{N-1}{k} + \sum_{k=0}^{N-1} k\binom{N-1}{k} = 2^{N-1} + (N-1)2^{N-2} = 2^{N-1}(2+(N-1)/2)$. Plugging this rewritten denominator into (4) yields the specification for a linear p. ■

Proof of Proposition 4

Proof. Inefficiency follows from that fact that $B > C$.

(i) The probability mass of players i with signal $b_i < \bar{b}$ is decreasing in B for all $\bar{b}$. Hence, in particular it is for $\bar{b} = b^*$. Finally, since p is increasing in n, the number of players for whom $b_i < b^*$ decreases the probability of successful disease control.

(ii) For all $B < b^*$, there exists a $\varepsilon > 0$ small enough such that $B + \varepsilon < b^*$. But $b_i \leq B + \varepsilon$ for all i. Yet $x_i^*(b_i) = 0$ for all $b_i < b^*$. Given $C < B$, the result follows. ■

Proof of Proposition 5

Proof. Immediate from combining the fact that $p(0) = 0$ and $p(N) = 1$ with the equilibrium strategy given in Theorem 1. ■

Proof of Theorem 2

Proof. Fix $\bar{n}$. $F(B; b_i)$ still corresponds to the posterior on B, conditional on b_i. Now, however, let $G(n; B, \beta, \bar{n})$ denote the density of n, conditional on B *and* assuming all players $j\{\bar{n}+1, \bar{n}+2, ..., N\}$ play strategy $x_j(b_j) = 0$ for all $b_j < \beta$ and $x_j(b_j) = 1$ for all $b_j \geq \beta$, while all players $i \in \{1, 2, ..., \bar{n}\}$ play the strategy as given by assumption for the coalition. The posterior G is still continuous in all of its arguments. It is immediate that $G(n; B, \beta, \bar{n}) \geq G(n; B, \beta, \bar{n}') \iff \bar{n}' \leq \bar{n}$, for all B, where the inequality is strict if $\bar{n}' < \bar{n}$ and $\beta \in [B - \varepsilon, B + \varepsilon]$. Moreover, note that the case of no coalition (Theorem 1) corresponds to $\bar{n} = 0$ in the extended model.

It therefore must be that for $\bar{n} > 0$, for all b_i, we have $\iint u_i(x_i; B, n)\, dG(n; B, \beta, \bar{n})\, dF(B; b_i) \geq \iint u_i(x_i; B, n)\, dG(n; B, \beta, 0)\, dF(B; b_i)$, which inequality is strict whenever $b_i \in [\beta - 2\varepsilon, \beta + 2\varepsilon]$. But this means that:

$$\iint u_i(x_i; B, n)\, dG(n; B, b^*, \bar{n})\, dF(B; b^*) > \iint u_i(x_i; B, n)\, dG(n; B, b^*, 0)\, dF(B; b^*) = 0, \tag{8}$$

implying that there exists a $b^*(\bar{n}) < b^*$ for which $\iint u_i(x_i; B, n)\, dG(n; B, b^*(\bar{n}), \bar{n})\, dF(B; b^*(\bar{n})) = 0$. But defining $b^*(\bar{n})$ this way, we can conclude (by the same argument as for Lemma 3 in the proof of Theorem 1) it is a unique equilibrium strategy for all players $i \in \{\bar{n}+1, \bar{n}+2, ..., N\}$ to play the strategy given in Theorem 2.

Finally, from the monotonicity of G it is clear that $b^*(\bar{n})$ is decreasing in $\bar{n}$. ■

Proof of Proposition 6

Proof. Immediate from the fact that $b^*(\bar{n}) \leq b^*$ ($B_0 < b^*$), combined with equilibrium strategies for players outside the coalition (in the coalition). ■