Efficient Epidemics: Contagion, Control, and Coordination in a Global Game

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October 7, 2020

We're both on the market this year, so...

Introduction

Motivation

- Pandemics carry significant social and economic costs.
    - **Why do some diseases go epidemic whilst others are kept at bay?**
    - **Pure biology/epidemiology? Or economics as well?**
    - **How to avoid the next epidemic?**

This paper

- We study epidemic policy using a game theoretic model featuring:
  - Incomplete information about the disease
  - Strategic complementarity in eradication efforts
- Uncertainty + strategic complementarity = *global game*
  - Carlsson & Van Damme (1993, ECTA), Morris & Shin (1998, AER)

Model

Building Blocks

- N countries, labeled i.
- Binary action x_i: effort to eradicate ($x_i = 1$), or not ($x_i = 0$).
- Cost of eradication effort: C.
- Benefit of eradication: $B \in [\underline{B}, \overline{B}]$, drawn uniformly.
- True B unobserved. Countries observe private signal $b_i \in [B - \varepsilon, B + \varepsilon]$, $\varepsilon > 0$, drawn uniformly.
- **Probability of successful eradication**, given n countries take efforts, is $p(n)$, with $p' \geq 0$, $p(0) = 0$ and $p(N) = 1$.

Payoff

The payoff to country i, given n countries $j \neq i$ play $x_j = 1$, is:

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

normalized so that the payoff to no eradication ($x_i = 0$) is zero.
Since B is unobserved, i chooses x_i to maximize:

$$u_i^e(x_i; b_i, n) = [p(n + x_i) \cdot b_i - C] \cdot x_i. \quad (2)$$

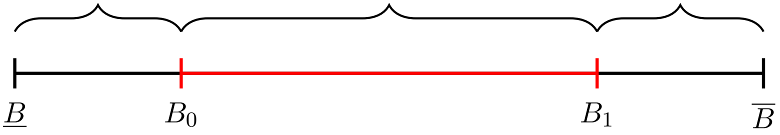
Tie-breaking rule: play $x_i = 1$ if $u_i^e = 0$; inconsequential.

A Priori Support of B

$B < B_0$
never eradicate

$B \in (B_0, B_1)$
national best-responses
mutually dependent

$B > B_1$
always eradicate



strict dominance region

coordination game (multiple equilibria)

strict dominance region

- Social planner: eradication for $B \geq B_0$, no eradication for $B < B_0$

Timing

The structure of the game is *common knowledge* and as follows:

1. Nature draws a true $B \in [\underline{B}, \overline{B}]$.
2. Each $i \in \{1, 2, ..., N\}$ receives private signal b_i of B.
3. All $i \in \{1, 2, ..., N\}$ simultaneously choose action $x_i \in \{0, 1\}$.
4. Payoffs are realized according to B and the actions chosen by all players.

Results

Theorem: Unique Equilibrium

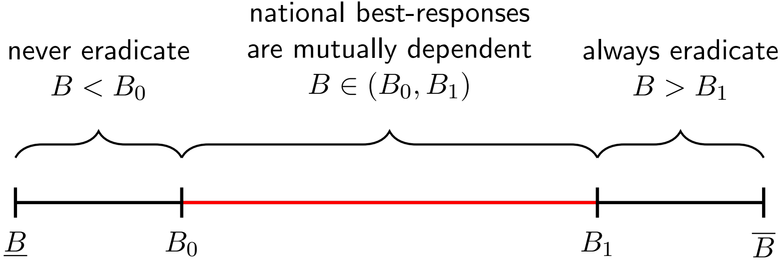
Theorem

The game has a unique Bayesian Nash equilibrium. Let x_i^* *denote the associated equilibrium strategy for country* i*. Then there exists a unique* $b^* \in (B_0, B_1)$ *such that, for all* $i \in \{1, 2, ..., N\}$*:*

$$x_i^*(b_i) = \begin{cases} 1 & \textit{if} \quad b_i \geq b^* \\ 0 & \textit{if} \quad b_i < b^* \end{cases}. \tag{3}$$

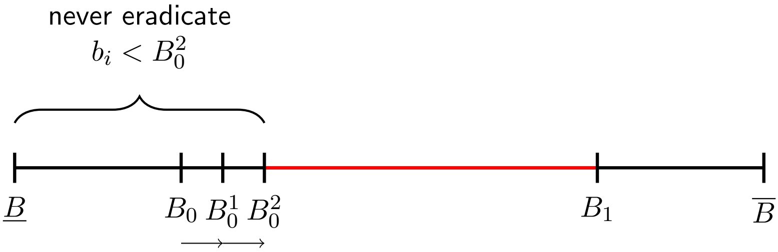
The result is actually stronger: there is one and only one strategy surviving iterated elimination of dominated strategies. The associated strategy-profile x^* hence has to be the unique BNE, or any type of self-referential equilbrium concept based on Nash. It is therefore also *rationalizable* in the sense of Bernheim (1984, ECTA) and Pearce (1984, ECTA).

Intuitive Proof: recall support of B

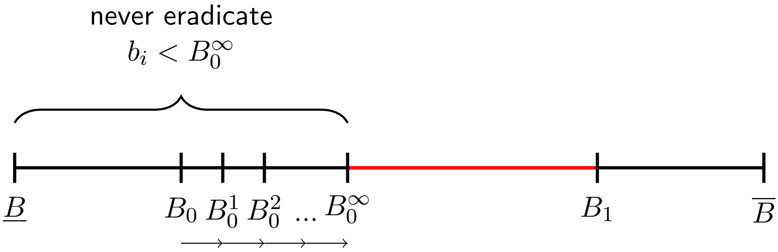


Intuitive Proof: extending the no-eradication region at B_0

Intuitive Proof: extending the no-eradication region at B_0^1

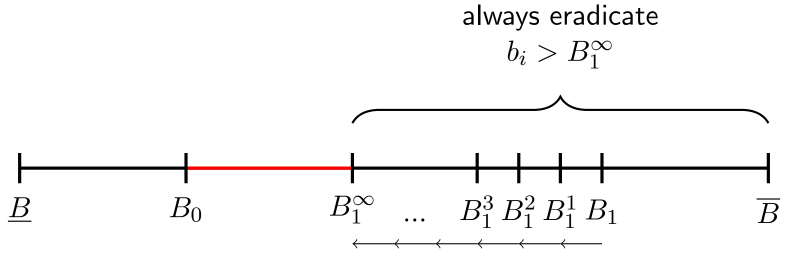


Intuitive Proof: extending the no-eradication region to B_0^∞



Intuitive Proof: extending the eradication region at B_1

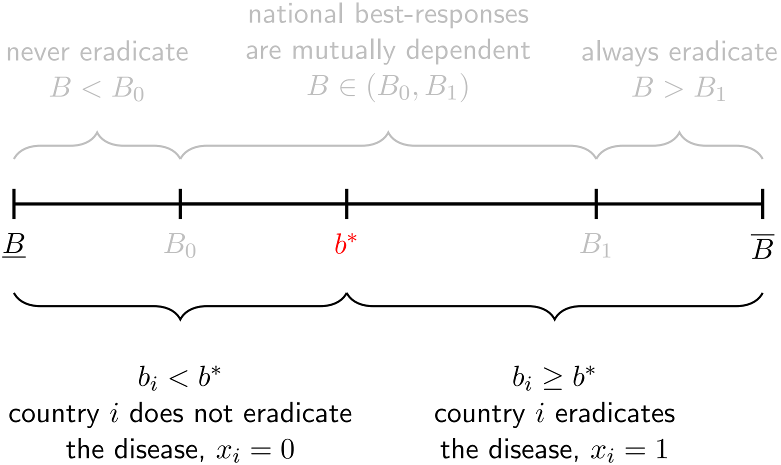
Intuitive Proof: extending the eradication region to B_1^∞



Why $B_0^\infty = B_1^\infty$?

- Suppose not, so $B_0^\infty < B_1^\infty$.
- Then, in expectation, $\mathbb{E}_n u_i^e(x_i = 1; b_i, n) = \mathbb{E}_n[p(n+1) \cdot b_i - C] > 0$ for all $b_i > B_0^\infty$, by the definition of B_0^∞.
- Similarly, $\mathbb{E}_n u_i^e(x_i = 1; b_i, n) = \mathbb{E}_n[p(n+1) \cdot b_i - C] < 0$ for all $b_i < B_1^\infty$, by the definition of B_1^∞.
- But if $B_0^\infty < B_1^\infty$, then there must exist at least one b_i for which $\mathbb{E}_n u_i^e(x_i = 1; b_i, n) < 0 < \mathbb{E}_n u_i^e(x_i = 1; b_i, n)$.
- This is a contradiction.
- Hence $B_0^\infty = B_1^\infty$.

Intuitive Proof: $B_0^\infty = B_1^\infty = b^*$



Paradox 1: Inefficiency

Proposition (Inefficiency)

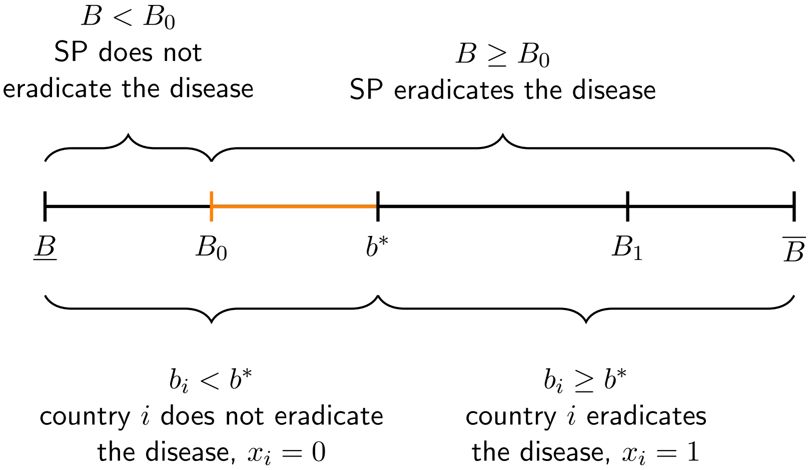
For all $B \in (B_0, b^*)$, a epidemic is inefficient. Moreover:

(i) *For $2\varepsilon < B_1 - B_0$, the probability of successful eradication is monotone increasing in the (true) eradication benefit B.*

(ii) *For ε sufficiently small, for all $B \in (B_0, b^*)$, there will be a rational but inefficient epidemic.*

Note: not possible to make a stochastic dominance statement with multiple equilibria!

Inefficiency, illustrated



Paradox 2: Less is more

Corollary (Speed bump effect)

More lethal diseases ($B > b^* + \varepsilon$) cause fewer deaths than less lethal ones ($B < b^* - \varepsilon$).

- Fatality rate SARS: $\sim 10\%$. Fatality rate COVID-19: $\sim 0.5\%$.
- Death toll SARS: < 900. Death toll COVID-19: $> 424,000$, and counting.

Theorem: Unique Equilibrium, Heterogeneous Countries

Let C_i and B_i denote the country-specific eradication cost and benefit, respectively.

Theorem (Heterogeneous countries)

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

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

Global Disease Eradication

Policy challenge

How to make sure disease get eradicated when eradication is efficient?

Commitment

- A subset of $\bar{n} \leq N$ countries forms a coalition.
- WLOG, coalition consists of countries $i \in \{1, 2, ..., \bar{n}\}$
- Prior to an outbreak, they **commit** to strategy:

$$x_i^c(b_i) = \begin{cases} 1 & \text{if} \quad b_i \geq B_0 \\ 0 & \text{if} \quad b_i < B_0 \end{cases}.$$

- That is: promise to take eradication efforts whenever eradication is (perceived to be) globally efficient.
- Note: The coalition could in principle commit to any threshold $b^c \in [B_0, b^*]$. Our result would mutatis mutandis hold true.

Unique But Better Equilibrium

Theorem (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 there exists a unique (conditional on $\bar{n}$) $b^*(\bar{n})$ such that, for all $i \in \{\bar{n}+1, ..., N\}$:

$$x_i^*(b_i) = \begin{cases} 1 & \textit{if} \quad b_i \geq b^*(\bar{n}) \\ 0 & \textit{if} \quad b_i < b^*(\bar{n}) \end{cases} . \tag{5}$$

Moreover, $b^*(\bar{n})$ is monotone decreasing in $\bar{n}$, with $b^*(0) = b^*$ and $b^*(N) = B_0$.

For countries $i = 1, 2, ..., \bar{n}$, the strategy is given by assumption.

Greater Coalitions Make For Fewer Epidemics

Proposition (Inefficiency with a coalition)

For all $B \in (B_0, b^*(\bar{n}))$, a epidemic is rational but inefficient. Moreover, the probability of an inefficient but rational epidemic is decreasing in $\bar{n}$, the number of countries in the coalition.

Conclusions

Summary

- We study international epidemic policy in a global game
- Our game has a unique equilibrium, which may:
  - imply a "rational epidemic"
  - be inefficient
  - cause more deaths from less lethal diseases
- International epidemic policy:
  - Prior to an outbreak, a subset of players (e.g. countries) commits to eradication.
  - Still a unique equilibrium.
  - Probability of inefficient rational epidemic decreasing in coalition size

Thank you!

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