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Climate Change and Pandemics:

On the Timing of Interventions to Preserve a Global Common

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Climate Change and Pandemics: On the Timing of Interventions to Preserve a Global Common*

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Abstract

We characterize timing choices in investments towards the conservation of a global common and derive implications for interventions to contain the spread of a contagious disease.

1 Introduction

The opportunity cost of irreversible investments under uncertainty includes the forgone value of the option to wait for new information before undertaking the investment (Weisbrod, 1964; McDonald and Siegel, 1986). Policy interventions aimed at preserving global commons typically involve some degree of irreversibility. Since the extent of the depletion of the global common and of the damages this may cause are not well understood ex ante, with new information being learnt as time goes by, delaying action has a

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positive option value, which must be weighed against its potential costs – more severe damages from waiting and/or higher costs of future investments towards conservation.

However, when the benefits or costs from an irreversible investment are not fully internalized by individual decision-makers, the timing of decentralized investment choices can diverge from the timing that is collectively optimal: external benefits will lead to overly-cautious decisions (too much learning), while external costs will lead to overly-rushed decisions (too little learning). Thus, lack of cooperation over conservation measures in relation to a global common can result in excessive delay rather than (or in addition to) sub-optimal levels of intervention. Implications for global governance are self-evident. This conclusion follows from a straightforward application of standard solution concepts for non-cooperative games (Nash, 1951) to an option value problem. But while the concept of option value has been invoked in relation to the conservation of natural resources (e.g., Krutilla, 1967), the consequences of non-cooperative decision-making for the timing of investment, to the best of our knowledge, have not been highlighted before.

Section 2 sets out the basic structure of a generic two-period commons investment problem. Section 3 compares the cooperative and non-cooperative timing of interventions in a model of epidemic contagion. Section 4 concludes.

2 The timing of investment in a two-period commons problem

The investment timing problem we have outlined and the conclusions that follow from its analysis can be most easily illustrated by reference to a two-agent, two-period commons problem.

There are two decision-makers, each having to make an investment that can be carried out either at time $t = 0$ or at time $t = 1$. There are two states of the world, L and H. In state L, the value of investment is zero to both decision-makers. In state H, the private present value, evaluated at $t = 0$, of the investment to the investor is $v/2 \geq 1$ if the investment is carried out at $t = 0$ and is $\delta\rho v/2$ if it is carried out at $t = 1$, with $\delta < 1$ representing a discount factor, and with $\rho \leq 1$ reflecting an attenuation (beyond dis-

counting) in the efficacy of investment if this is delayed. Benefits of the same size from the investment also accrue to the other decision-maker in state H, making the collective value of the investment equal to v and $\delta\rho v$ respectively in each of the two periods. In relation to both climate change and pandemics, the value of the investment would consist of a reduction in future damages that can result from current conservation measures; and the attenuation in the value of delayed investment, as reflected by $\rho \leq 1$, would correspond to the potential increase in the severity of damages from delaying action (higher terminal temperatures, higher prevalence of infections).

At $t = 0$ the two decision-makers hold a common belief, β, about the likelihood of state H occurring. At $t = 1$ the state of the world is fully revealed.

If the investment is carried out at $t = 0$, the cost of the investment (at $t = 0$) is unity; if it is carried out at $t = 1$, the cost (at $t = 1$) is $\gamma < 2$. In the discussion that follows, we assume that $\rho v/2 > \gamma$, which implies that if investment has not occurred at $t = 0$ and the state is revealed to be H at $t = 1$, investing at $t = 1$ is always individually optimal, i.e. there cannot be an outcome where investment never takes place. This assumption also implies $\rho v > 1$ and $v > \gamma$, i.e. if investment has not occurred at $t = 0$ and the state is revealed to be H at $t = 1$, investing at $t = 1$ is jointly optimal; and if $\beta = 1$ (at $t = 0$, investors know with certainty that the state is H), then investing at $t = 0$ is jointly optimal. This means that the only choice that we need to consider, from both a collective and an individual perspective, is whether investment should take place at $t = 0$ or at $t = 1$, rather than whether or not investment should take place at all.

Cooperative choice

Consider first the jointly optimal investment timing choice. The joint expected payoff (the payoff of a representative player) from joint investment at $t = 0$ is $\beta v - 1$, whereas the joint expected payoff, evaluated at $t = 0$, from waiting and investing at $t = 1$ if H is realized (which occurs with probability β) is $\delta\beta(\rho v - \gamma)$. Equating these two values, we can solve for a critical level of β above which it will be jointly optimal to act at $t = 0$

and below which it will be jointly optimal to delay:

$$\beta^C = \frac{1}{\delta\gamma + (1-\delta\rho)v}. \tag{1}$$

This is decreasing in v, i.e. for a given investment cost, it will be optimal to act under a less precise prior the higher is the potential value, v, of the investment.

Decentralized choice

We next consider decentralized choices and derive conditions under which investment at $t = 0$ by both parties is a Nash Equilibrium. Let $a_t^i \in \{0, 1\}$ denote the investment choice by investor i at t. Under the assumption $\rho v/2 > 1$, each investor will always invest at $t = 1$ in state H if she has not invested at $t = 0$, implying $a_1^i = 1 - a_0^i$. Then the expected private payoff (evaluated at $t = 0$) to i from investing at $t = 0$ is

$$\mathrm{E}\Pi^i\left(a_0^i = 1,\, a_0^{-i}\right) = \beta\left(1 + a_0^{-i}\right)v/2 - 1 + \delta\beta\rho\left(1 - a_0^{-i}\right)v/2, \tag{2}$$

(with $-i$ denoting the other investor), and the expected private payoff from postponing the investment to $t = 1$ (while benefiting immediately from any investments made by the other party at $t = 0$) is

$$\mathrm{E}\Pi^i\left(a_0^i = 0,\, a_0^{-i}\right) = \beta\, a_0^{-i} v/2 + \delta\beta\left(\rho(2 - a_0^{-i})v/2 - \gamma\right). \tag{3}$$

Equating these two expressions, we can solve for a critical level of β above which investment at $t = 0$ by both parties is a Nash Equilibrium and below which it is not:

$$\beta^N = \frac{1}{\delta\gamma + (1-\delta\rho)v/2}. \tag{4}$$

Thus, if $\beta \in (\beta^C, \beta^N)$, taking action at $t = 0$ is jointly optimal but the non-cooperative outcome involves postponement to $t = 1$: action will eventually take place (in the unfavorable realization), but it will happen too late, producing a lower ex-ante net return. Note that this can even occur for $\gamma = 1/\delta$, i.e. when the present value of the gross cost of investing at $t = 0$ is *less* than that of investing at $t = 1$.

Atomistic agents

The previous results have been derived for a game involving a finite number of players. This is the right setting for modelling situations where the decision-makers are institutional players, such as the governments of different sovereign countries. But a problem with the same structure could arise in an environment with a large number of atomistic players whose individual actions have negligible impact on other players – what could be described as a "competitive" environment with externalities. This would be the right setting to use when the investment choices that affect the global common are made by private-sector agents.

To see how the previous conclusions can carry over to such a setting, consider a unit mass of players, and let $a_t(i) \in \{0, 1\}$ denote the investment choice of player $i \in [0, 1]$, and suppose that the effect of all players' investment choices at t on player i's period-t payoff, gross of the cost of the investment, equals $\left(\omega a_t(i) + (1 - \omega) \int_0^t a_t(j)\, dj\right) v$, with $\omega \in (0, 1]$. Proceeding as before, we obtain an expression for β^C that coincides with (1), whereas the expression for β^N becomes

$$\beta^N = \frac{1}{\delta\gamma + (1 - \delta\rho)\omega v}. \tag{5}$$

In order to bridge the gap between the privately optimal and socially optimal timing of investment, a central planner could in this case resort to a Pigouvian remedy that either taxes investment in the second period and/or subsidizes investment in the first period.

3 Delaying epidemic contagion

The discussion that follows examines the investment timing problem in the context of a stylized, infinite-horizon model of epidemic contagion. The basic relationships that define the process of contagion reflect those that have been described in the epidemiological literature (Anderson and May, 1979), but these are augmented by a dynamic model of costly intervention choices.

Contagion

There is a unit mass of identical, infinitely-lived individuals. At time t, each individual, if not already immune, contracts a contagious disease with probability

$$\phi_t = \kappa\, l_t\, (1 - a_t), \quad \kappa \in (0, 1], \tag{6}$$

where l_t denotes the proportion of individuals in the population that have contracted the disease at t or in any previous period and have survived from it, and $a_t \in (0, 1)$ reflects the severity of the delaying measures adopted at t. Mathematical models of epidemic contagion typically also account for how the immunization of recovered individuals can limit further contagion. For the sake of simplicity, the discussion that follows will abstract from this effect.[1] A version of the model where survivors can become non-infectious (presented in the appendix) leads to qualitatively similar conclusions.

An individual contracting the disease at t becomes ill at $t + 1$ and remains ill for one period, dying in the same period with probability θ. If a diseased individual survives to the following period, she becomes immune and can no longer contract the disease. Thus, the cumulative number of infections at $t + 1$ equals

$$q_{t+1} = q_t + \phi_t\, (1 - q_t), \tag{7}$$

the number of deaths at $t + 1$ is

$$d_{t+1} = \theta\, (q_{t+1} - q_t), \tag{8}$$

and the number of recovered survivors is

$$l_{t+1} = (1 - \theta)\, q_{t+1}. \tag{9}$$

Framing the above relationships in terms of the categories employed in Susceptible-Infectious-Recovered (SIR) models of contagion, $1 - q_t$ corresponds to the Susceptible, q_t to the infected, and $(1 - \theta)\, q_t$ to the Infectious (the survivors, who are assumed here to remain indefinitely contagious), and $\theta\, q_t$ to the Recovered (the deceased), with with $q_{t+1} - q_t$ representing the number of currently diseased individuals.

[1] An implication of this simplification is that "herd immunity" is only ever achieved if $a_t = 1$ (or if $\theta = 1$, i.e. all individuals who contract the disease die).

Payoffs

Each infection entails a private and social cost of η in all periods following infection until a cure is discovered (if it is discovered), with each death entailing an additional private and social cost of unity in the period in which it occurs; the overall (negative) social value of infection at t is therefore

$$v_t = -d_t - \eta\, q_t. \tag{10}$$

Intervention at level a_t has a private and social cost of

$$g_t = -\zeta \ln\left(1 - \gamma {a_t}^2\right) \equiv h(a_t), \tag{11}$$

with $\gamma \in (0, 1]$. This cost schedule exhibits the following properties: $h'(a_t) \geq 0$, $h''(a_t) > 0$, $h'(0) = 0$, $\lim_{\gamma \to 1} h(1) = \infty$.

Information structure

There are two possible states of the world. In state $s = 1$ in each period a cure becomes available with probability π; in state $s = 0$, a cure can never be found. The state of the world is not directly observable. The prior belief at $t = 0$ that a cure can be found, i.e. that the state of the world is $s = 1$, $\beta_0 \in (0, 1)$. Let $\sigma_t = \{0, 1\}$ be an informative public signal received at t about s, with $\sigma_t = 1$ denoting that a cure has been discovered and $\sigma_t = 0$ denoting no discovery. The probabilities with which a signal $\sigma_t = 1$ is observed in each state are respectively $\Pr(\sigma = 1 \mid s = 1) = 1$ and $\Pr(\sigma = 1 \mid s = 0) = 0$; i.e. a signal $\sigma_t = 1$ fully reveals that the state state of the world is $s = 1$. The probability with which a signal $\sigma_t = 0$ is observed in each state are respectively $\Pr(\sigma = 0 \mid s = 1) = 1 - \pi$ and $\Pr(\sigma = 0 \mid s = 0) = 1$. Then, the (common) posterior belief at t of a cure being possible, if a cure has not yet been discovered at t, evolves as

$$\beta_t = \frac{\beta_0 (1 - \pi)^t}{\beta_0 (1 - \pi)^t + (1 - \beta_0)} = \frac{1}{1 + (1/\beta_0 - 1)(1 - \pi)^{-t}}. \tag{12}$$

This is decreasing in t: as time goes by, if a cure is not discovered, agents become more pessimistic about the possibility of a discovery ever occurring.

The belief at t of a cure becoming available next period is $\beta_t \pi$. An equivalent interpretation is that $1 - \beta_t \pi$ represents the belief of the infection developing into a damaging epidemic – and so, starting from an initial belief that the infection will cause limited damage, the arrival of new information suggesting that the infection will cause widespread damage will lead decision-makers to take the threat more seriously.

The planner's problem

Consider a utilitarian planner making decisions about the level of intervention at t. The planner's optimization problem can be expressed recursively as

$$V_t(q_t) = \max_{a_t} \; v_t - g_t + (1 - \beta_t \pi)\, \delta\, V(q_{t+1}). \tag{13}$$

with β_t satisfying (12); and where $V(q_{t+1})$ denotes the continuation value of the problem at t if a cure is not discovered at $t + 1$.

The optimal intervention policy, a_t, at time t depends on the current belief β_t, the cost of intervention, g_t, and the cost of the infected individuals, which is a function of the rate at which susceptible individuals become infected and the number of infectious individuals at $t - 1$. The FONC for an optimum choice of q_t at t is

$$-h'(a_t) + (1 - \beta_t \pi)\, \delta\, \frac{dV(q_{t+1})}{da_t} = 0. \tag{14}$$

where $h'(a_t) = (2\zeta\gamma a_t)/\left(1 - \gamma {a_t}^2\right)$. If the corresponding condition holds at $t + 1$, then, by the envelope theorem,[2] we must have

$$\frac{dV(q_{t+1})}{da_t} = \kappa(1 - \theta)(\eta + \theta)(1 - q_{t-1})q_{t-1}. \tag{15}$$

This allows us to re-write the FONC as

$$\Lambda_t(1 - q_{t-1})q_{t-1} - \frac{2\zeta\gamma a_t}{1 - \gamma {a_t}^2} = 0, \tag{16}$$

[2]The envelope theorem applies if a_{t+1} corresponds to an interior optimum choice at $t + 1$. The assumed cost structure guarantees that $a_t > 0$, and thus that a_t an interior solution as long as we focus on parameterizations for which a_t remains below unity.

where $\Lambda_t \equiv \delta\kappa(\eta+\theta)(1-\theta)(1-\beta_t\pi)$, giving

$$a_t = \frac{\sqrt{\gamma\Big(\zeta^2\gamma + \big(\Lambda_t(1-q_{t-1})q_{t-1}\big)^2\Big)} - \zeta\gamma}{\gamma\Lambda_t(1-q_{t-1})q_{t-1}} \equiv a_t^C. \tag{17}$$

In conjunction with (12), this delivers a socially optimum intervention schedule for a given initial prior, $\beta_0 < 1$, about the state of the world and initial condition q_0.

Decentralized intervention

Suppose next that there are M symmetric countries $i = \{1, \ldots, M\}$. Each country has a large population, and each of them makes a decision on the intervention measure to avoid/contain the spread of the disease. The cost of intervention for country i at level a_t at time t is still equal to $g_t^i = h(a_t^i) = -\zeta \ln\big(1-\gamma(a_t^i)^2\big)$; and in country i an individual contracts the disease, if not already immune, with probability

$$\phi_t^i = \kappa l_t\Big(1 - \Big(a_t^i \prod_{j\neq i} a_t^j\Big)^{1/M}\Big). \tag{18}$$

The number of newly individuals infected in country i at time t thus depends on i's chosen level of intervention as well as that of other countries. All the other country-specific variables evolve in each country following the rules described the previous section. The information structure is identical to that described in the previous section, with beliefs at time t being common across the players. If a cure is discovered in either country, both countries will make use of it without delay.

Conditions for a Markov-perfect Nash equilibrium (Maskin and Tirole, 1988) can be derived as follows. The continuation payoff at t of country i, if a cure has not been discovered in any of the previous periods, is

$$V_t^i(q_t^i) = \max_{a_t^i}\ v_t^i - g_t^i + (1-\beta_t\pi)\delta V_{t+1}^i(q_{t+1}^i), \tag{19}$$

where $V_{t+1}^i(q_{t+1}^i)$ is country i's the continuation payoff at $t+1$. Deriving the FONC associated with (19) and solving for the symmetric Markov-perfect Nash equilibrium

level of a_t, we obtain $a_t^i = a_t^N, i \in \{1, \ldots, M\}$, we obtain

$$a_t = \frac{\sqrt{\gamma\left(M^2\zeta^2\gamma + \left(\Lambda_t(1-q_{t-1}^N)q_{t-1}^N\right)^2\right)} - M\zeta\gamma}{\gamma\Lambda_t(1-q_{t-1}^N)q_{t-1}^N} \equiv a_t^N, \tag{20}$$

with $q_t^i = q_t^{-i} = q_t^N$, and where Λ_t is as previously defined. The common level of intervention, a_t^C that recursively maximizes expected payoffs for the two countries coincides with the planning optimum derived earlier (expression (17)). The larger is the number of countries (M), the larger is the difference between a_t^C and a_t^N before a cure is discovered (if a cure is discovered in period t, the cure is adopted without delay in both cases, and contagion stops).

When viewed from a collective perspective, countries independently deciding levels of intervention are excessively cautious and wait too much. Specifically, comparing the expression for a_t^C with the expression for a_t^N, it is easy to see that the level of intervention level under cooperation, in each period, is higher than the one chosen under non-cooperation if no cure has been discovered before t, i.e. $q_{t-1}^C = q_{t-1}^N \Rightarrow a_t^C \geq a_t^N$. Since players here choose a continuous level of intervention, we no longer have the clear-cut characterization of investment timing choices that was in evidence in the discussion of Section 2. Nevertheless, if we compare two paths along which a_t and q_t are both increasing with t, and such that a_t eventually reaches a certain level a' in both, then the above ranking implies that the level of intervention a' will be reached at an earlier point under cooperation than under decentralized decision-making.

To illustrate the comparative implications of cooperative and non-cooperative decision-making, it is useful to consider a parameterized example. Figure 1 shows optimal (solid line) and Markov-perfect equilibrium (dotted line) levels of intervention, along a path in which a cure is never discovered, for $M = 2$, $\theta = 0.2$, $\beta_0 = 0.99$, $\pi = 2/3$, $\delta = 0.95$, $\kappa = 5/8$, $\eta = 0.05$, and $\zeta = 0.01$, when γ (the parameter determining the size of intervention costs) is 0.8.

Not only is the level of intervention affected by a lack of cooperation (Figure 1), also the speed at which a given level of intervention is reached is different in the two scenarios (Figure 2). In both scenarios the level of intervention chosen in the early periods

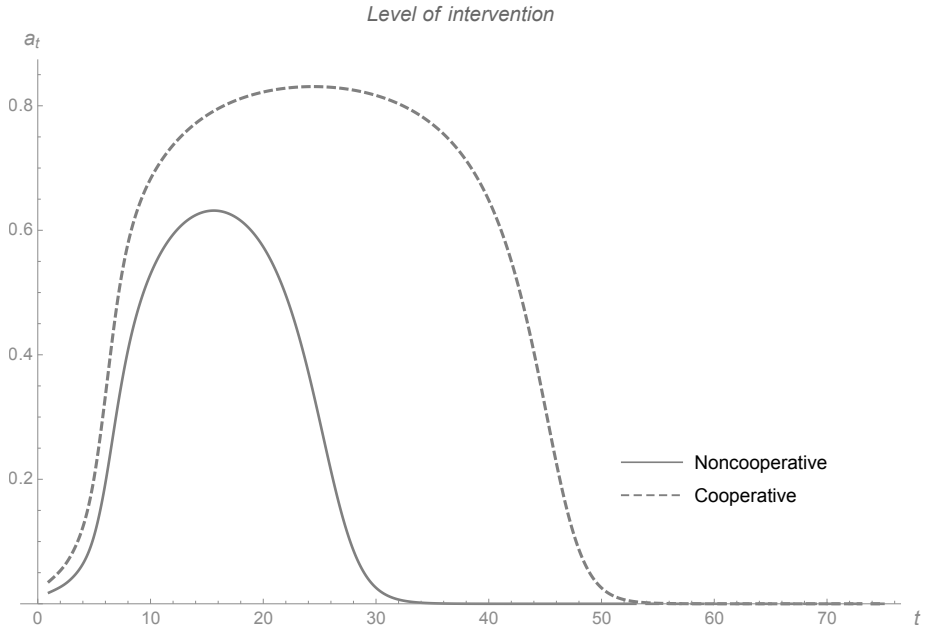

Figure 1: Optimal and noncooperative levels of intervention – high cost of intervention

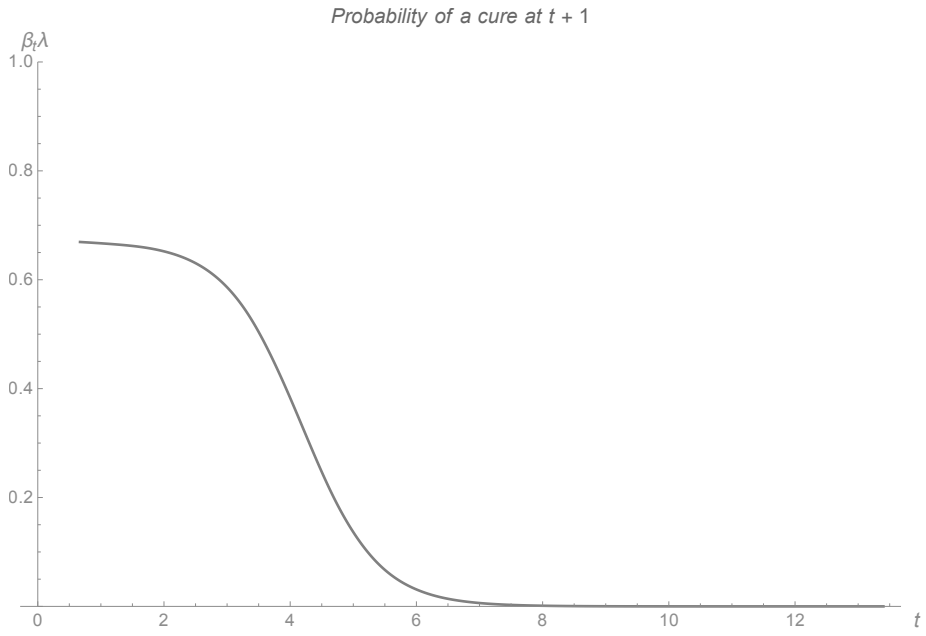

Figure 2: Timing of interventions – high cost of intervention

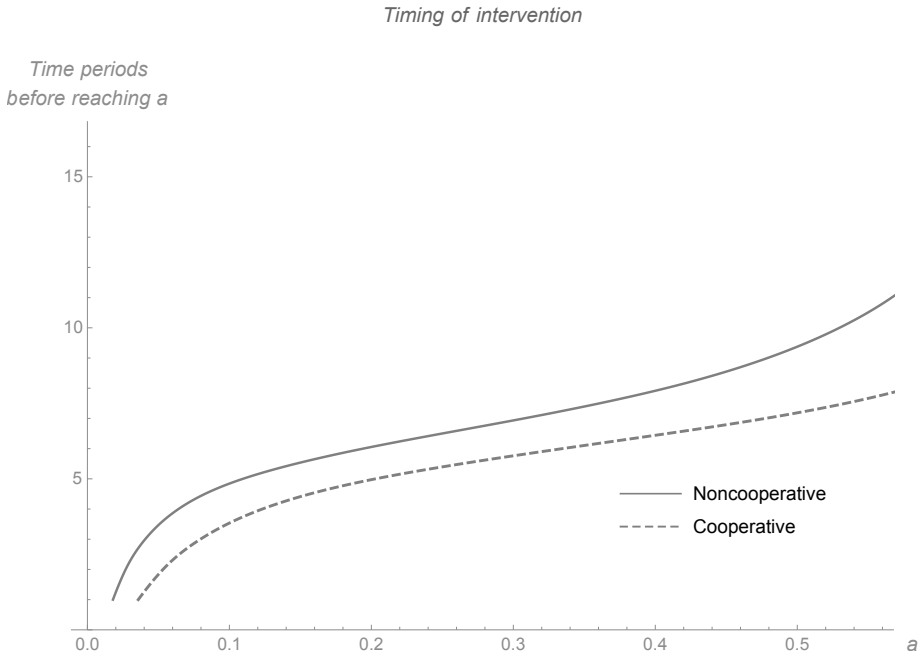

Figure 3: Beliefs about the probability of a cure at
– high cost of intervention

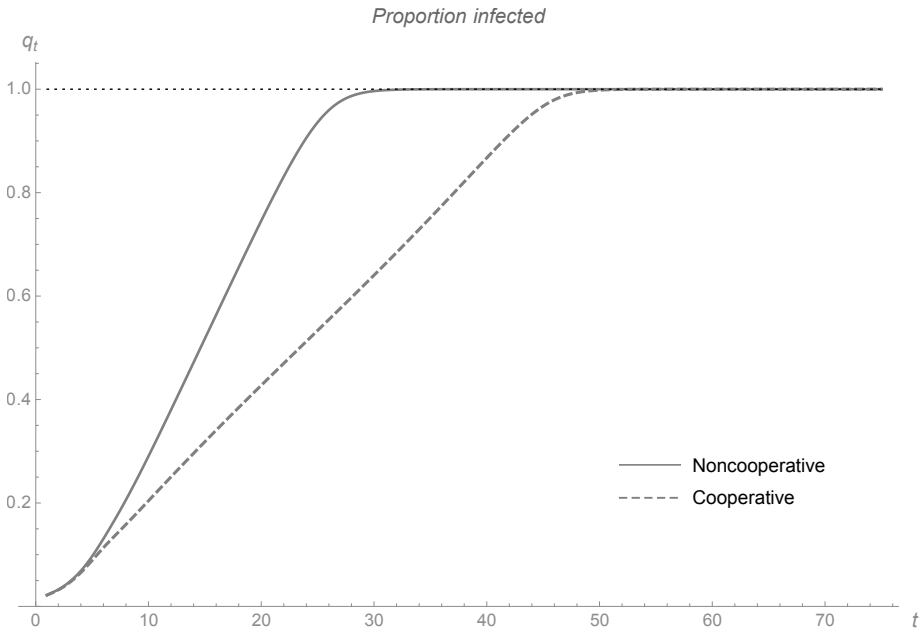

Figure 4: Spread of infection under optimal and noncooperative levels of intervention
– high cost of intervention

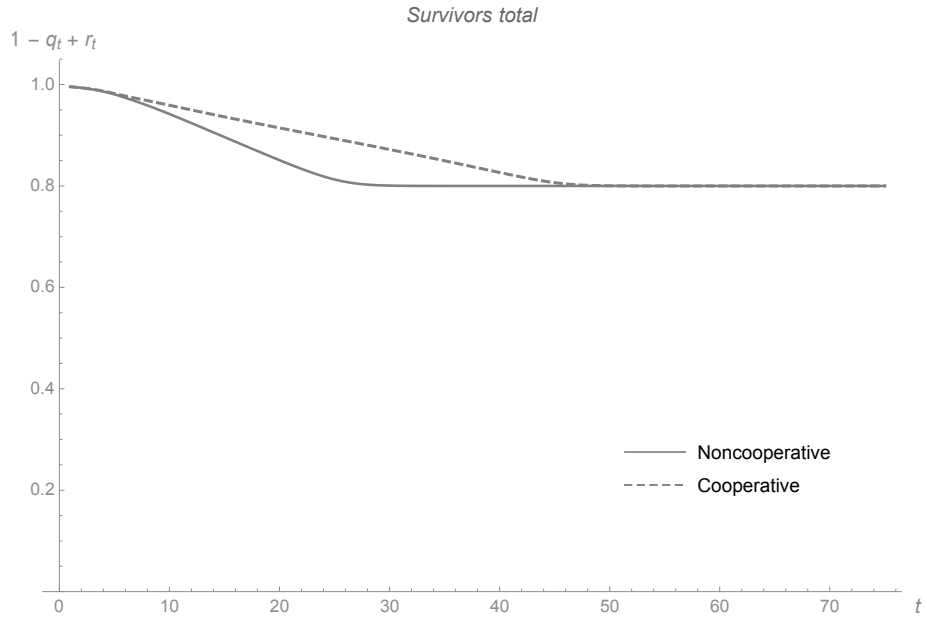

Figure 5: Proportion of survivors
under optimal and noncooperative levels of intervention
– high cost of intervention

of the epidemic, increases with t (despite the fact that players become more pessimistic with time about the possibility of finding a cure: Figure 3); but as players become more pessimistic, in both scenarios the level of intervention starts decreasing with time. Thus, equilibrium strategies are non-monotonic in t.

When the cost of intervention is sufficiently high (as is the case in this example), the anticipated flow of intervention cost for sufficiently pessimistic beliefs becomes higher and higher until it surpasses the anticipated damage caused by the infection (including deaths). Thus, in the long run, both the planner and the two countries end up adopting no intervention. Thus, the main difference between the two cases is in the speed at which a complete spread of contagion is reached: although the proportion of infected individuals is the same in the long run, maximum spread is reached more quickly under non-cooperation, and, in the transition to this maximum, the number of survivors is lower (Figures 4 and 5).

If we carry out the same comparison when the cost of intervention is lower ($\gamma = 0.6$),

then, as before, independent decision makers stop taking intervention measures when they become sufficiently pessimistic about the possibility of a cure, whereas a central planner never stops increasing its level of intervention even as it becomes more pessimistic. As result, the level of intervention (Figure 6) still evolves non-monotonically over time under non-cooperation, leading to maximum spread in the long run; whereas under cooperation, the (optimal) level of intervention keeps increasing until the spread of the disease is fully stopped and the proportion of infected individuals converges to a level that is below unity (Figure 7). Accordingly, the number of survivors in the long-run is higher under cooperation than under non-cooperation (Figure 8). In this case, lack of cooperation does not just affect the speed of transition to a given common long-run outcome; rather, it leads to a different long-run outcome.

Atomistic agents

We can use an almost identical analytical structure to characterize privately optimal choices by atomistic agents in relation to the prevention of contagion. Suppose that the probability of agent $i \in [0,1]$ becoming infected at t, if she has not yet contracted the disease, is

$$\phi_t(i) = \kappa l_t \left(1 - a_t(i)^{\omega} \, {A_t}^{1-\omega}\right), \quad \omega \in (0,1), \tag{21}$$

where $a_t(i)$ is the agent's own prevention effort, for which the agent incurs a cost $h\big(a_t(i)\big)$ as specified in (11), and where $A_t \equiv \exp\Big(\int_0^t \ln a_t(j)\, dj\Big)$. Proceeding as before, we obtain:

$$a_t = \frac{\sqrt{\gamma\left(\zeta^2\gamma/\omega^2 + \left(\Lambda_t(1-q_{t-1}^N)q_{t-1}^N\right)^2\right)} - \zeta\gamma/\omega}{\gamma\Lambda_t(1-q_{t-1}^N)q_{t-1}^N} \equiv a_t^N. \tag{22}$$

Lack of full internalization of the consequences of their prevention efforts leads agents to exert too little effort, unless they face corrective fines, f_t, for downwards deviations from a_t^C. The optimal level of such fines is that which makes an individual indifferent between choosing a_t^C or choosing a_t^N and paying the fine, i.e. $f_t = (1-\omega)\, h\big(a_t^C\big)$. The time path of optimal corrective fines will thus mirror the evolution of cooperative levels of intervention.

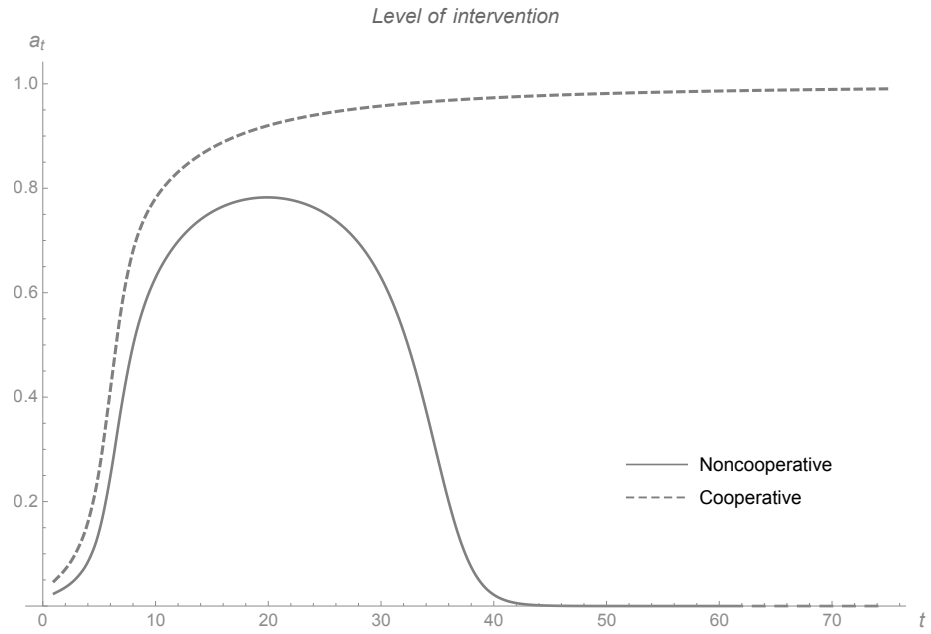

Figure 6: Optimal and noncooperative levels of intervention – low cost of intervention

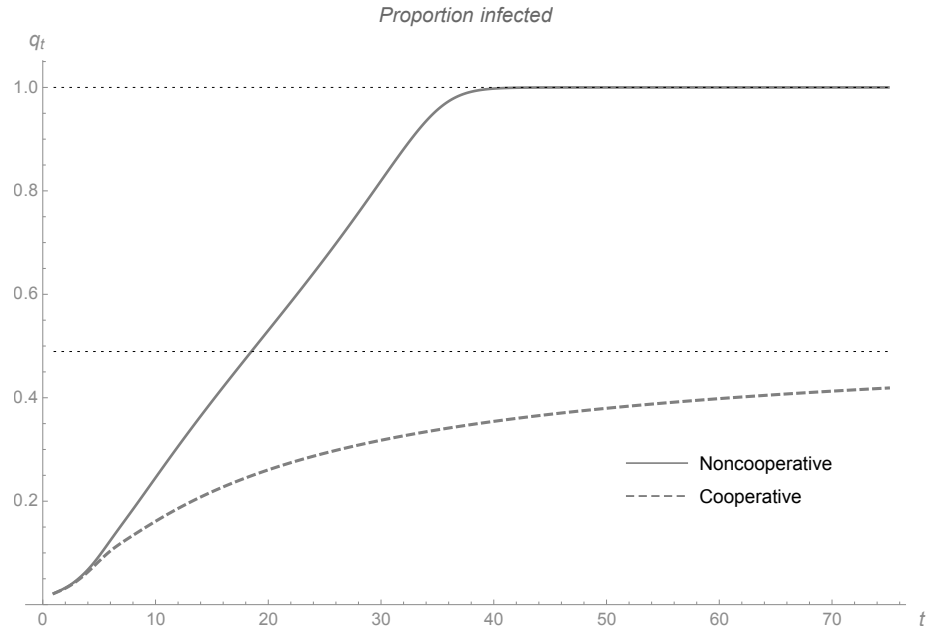

Figure 7: Spread of infection under optimal and noncooperative levels of intervention – low cost of intervention

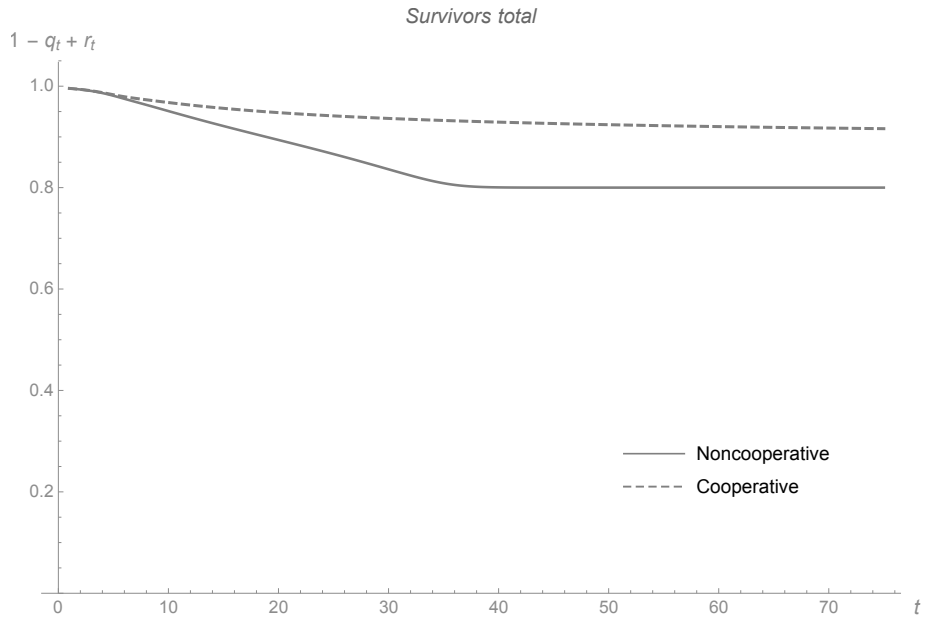

Figure 8: Proportion of survivors
under optimal and noncooperative levels of intervention
– low cost of intervention

4 Discussion

Managing global commons requires global cooperation, not just about whether action should be taken to preserve them, but also about when it should be taken. Lack of cooperation can result in excessive delay, even when decision-makers share common beliefs. The delay may be a matter of months and years in the case of climate change or a matter of days and weeks in the case of pandemics, but the structure of the problem remains the same.

The events that unfolded in 2020 suggest that, although the costs of contagion within national borders may have eventually been accounted for reasonably well, with most countries introducing similar containment measures, this might all have happened too late in comparison with the timing that might have been deemed to be optimal if transboundary effects had also been accounted for. The consequence might have been an above-optimal global loss of life and above-optimal long-run impacts on the global economy. And although shutting down borders removes one of the components of the transboundary externality, other dimensions remain for which a coordinated effort would be called for – for example in relation to the adoption of consistent standards of measurement and testing, which could improve the understanding of the process of contagion and help anticipate and prevent further outbreaks.

Global cooperation requires global institutions. In a commons problem such as the one we have described, if valuations are (at least in part) private, then designing optimal, incentive-compatible global cooperation institutions would be especially challenging. Arguably, this is one of the key obstacles delaying progress in multilateral negotiations on climate; but in relation to epidemic contagion, it is difficult to see how costs and benefits could be fundamentally heterogeneous across different regions of the world. Our analysis, however, has left out any costs and benefits to decision-makers that relate to political motives and incentives. That is perhaps where an explanation for the failure to coordinate the response to the pandemic can be found.

While all efforts to build multilateral institutions for the governance of global climate have so far produced disappointing results, where epidemics are concerned there have

been several instances of countries successfully cooperating – one of the first examples being the 1892 International Sanitary Convention for the control of cholera. As is the case for other supranational organizations, however, the WHO lacks the real powers that would be needed to force countries to take action. A concrete and manageable way forward could be for the WHO to start producing regularly updated rating scores for the epidemic risk conditions of individual countries (accounting both for current levels of contagion and for the readiness of countries to anticipate, contain and manage any new epidemics), much as global credit rating agencies do for sovereign debt. Not only could this induce countries to act more swiftly to contain future pandemics, but could also help restore confidence and speed up economic recovery in the post-lockdown phase.

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A Cooperative and noncooperative action in a SIR model of epidemic contagion

The state variables of a canonical SIR model of contagion are the proportion of susceptible individuals, S_t, proportion of infectious individuals, I_t, and the proportion of recovered individuals, R_t, with $S_t + I_t + R_t = 1$.

Consistently with the treatment in the main text, but allowing for a fraction, ρ, of infected individuals who survive to the following period to cease to be infectious, the proportion of newly infected individuals at t is

$$\Delta I_t^+ = \kappa \left(1 - A_t\right) I_t \, S_t, \tag{23}$$

where

$$A_t \equiv \left(\prod_i a_t^i\right)^{1/M}, \tag{24}$$

and where M is the number of countries. The change in the proportion of recovered (or deceased) individuals at t (from t to $t+1$) is

$$\Delta R_t = (\theta + \rho) \, I_t; \tag{25}$$

the change in the proportion of infectious individuals is

$$\Delta I_t = -\Delta R_t + \Delta I_t^+; \tag{26}$$

and the change in the proportion of susceptible individuals is

$$\Delta S_t = -\Delta R_t - \Delta I_t = -\Delta I_t^+. \tag{27}$$

All variables above, except for the levels of intervention, refer to the combined population of all countries.

Adopting the same specification of costs and benefits described of the analysis in the main text, the expressions for symmetric cooperative and noncooperative levels of intervention coincide with the expressions q_{t-1} and $1 - q_{t-1}$ being replaced respectively by I_t and S_t.

Time paths under cooperative and noncooperative intervention for all state and control variables (contingent on a cure not being discovered) are shown in Figures 9 and 10 for an example with $M = 4$, $\theta = 0.05$, $\rho = 0.1$, $\zeta = 0.01$, $\beta_0 = 0.95$, $\pi = 1/4$, $\delta = 0.9$, $\kappa = 1/3$, $\eta = 0.05$, $\zeta = 0.01$, and $\gamma = 0.15$. Intervention is higher under cooperation, and it occurs sooner. Note that, while this (optimally) slows down the spread of the disease in comparison with the noncooperative case, a byproduct of the slower contagion is a slower recovery.

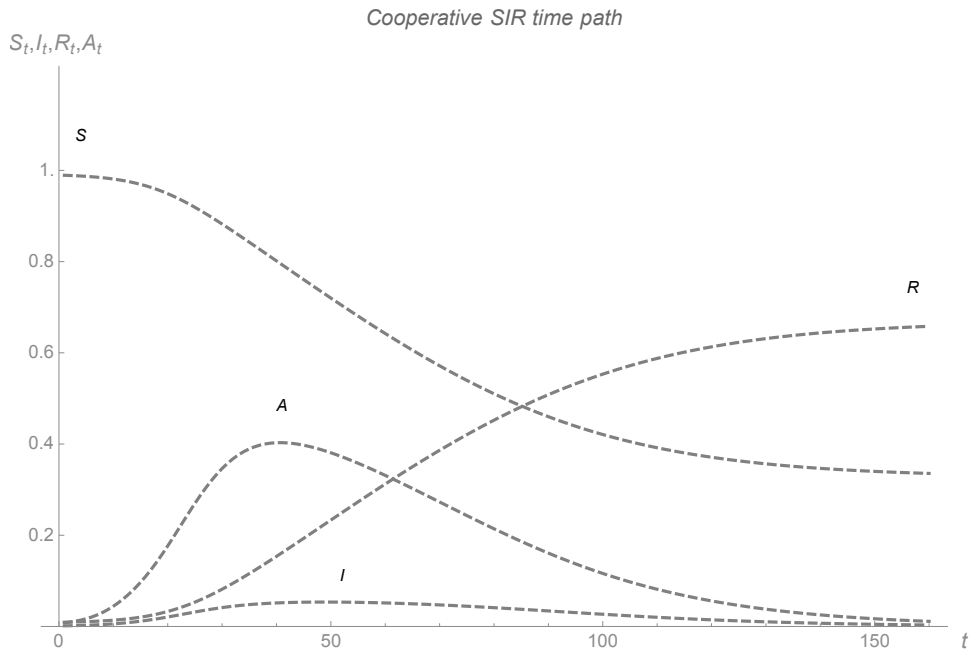

Figure 9: Susceptible-Infectious-Recovered paths under cooperative intervention

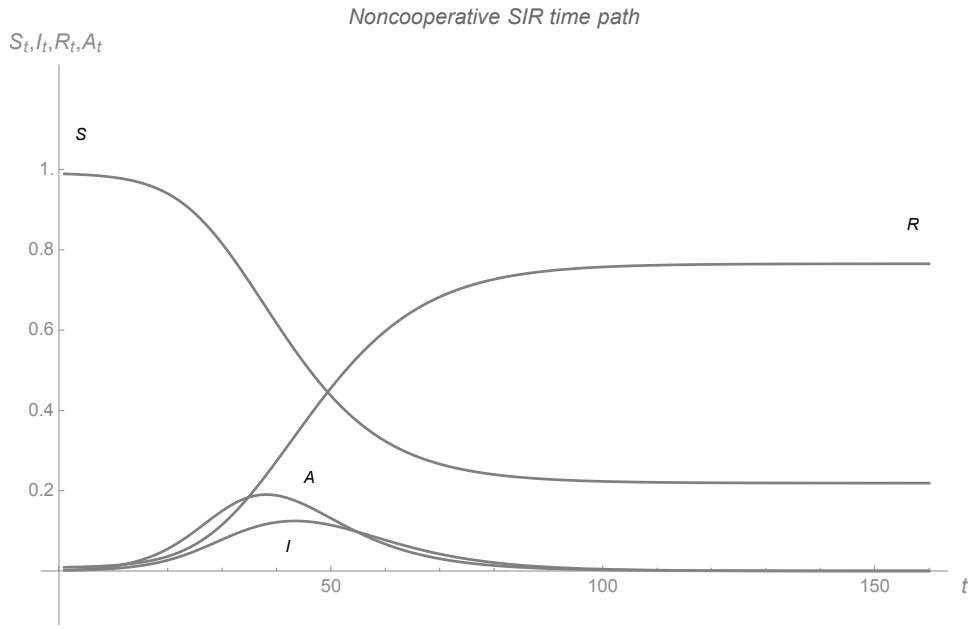

Figure 10: Susceptible-Infectious-Recovered paths under noncooperative intervention