Incentives for surveillance and reporting of infectious disease outbreaks

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Abstract. Containment of potential pandemic threats such as SARS and avian flu depends on prompt reporting of outbreaks. This paper examines the incentives of source countries to identify and disclose outbreaks. The analysis yields a number of policy-relevent findings. Whereas sanctions by trading partners following the formal report of an outbreak discourages reporting, sanctions based on fears of an undetected or unreported outbreak encourage disclosure by reducing the relative cost of reporting. Improving the quality of diagnostic technologies or the veracity of rumors of outbreaks may discourage disclosure by encouraging trading partners to raise sanctions following the report of an outbreak.

1 Prologue

In November 2002, health authorities in Guangdong Province reported a cluster of atypical pneumonia cases to China's National Ministry of Health in Beijing. In late February 2003, an infected medical doctor from Guangdong spent a single night on the ninth floor of a Hong Kong hotel and infected at least 16 other persons

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visiting his floor. The others included a tourist from Toronto, a flight attendant from Singapore and a businessman who later traveled to Vietnam. From this single event, severe acute respiratory syndrome (SARS) spread internationally. By May 2003, there were 7,000 infected in 30 countries. During the height of the global epidemic, more than 200 new cases were being reported each day. By the time the contagion was brought under control in June 2003, over 600 people died (WHO May 20, 2003).

Despite the early report from Guangdong, China did not report the outbreak of atypical pneumonia to the World Health Organization (WHO) until early February 2003. And though Chinese scientists had uncovered evidence linking SARS to a new coronavirus that same month (Science July 18, 2003), they did not allow WHO teams to visit Guangdong until early April. As a result, WHO scientists were not able to established the coronavirus link for themselves until mid-April (WHO July 4, 2003). Had the Chinese government reported the outbreak and its likely cause earlier, many hundreds of lives could have been saved. Had the disease been more virulent than it turned out to be, the effects of secrecy and delayed reporting by China could have been much more severe.

2 Introduction

In this paper we explore the incentives of countries to surveil their populations for infectious diseases and report outbreaks to international health authorities such as WHO and to other countries. Even a cursory analysis reveals that countries with a possible disease outbreak face conflicting incentives to report the outbreak. On the one hand, reporting may cause trading partners to impose *ex post* trade sanctions to limit the spread of disease to their borders. These sanctions impose large economic costs on the reporting country.[1] On the other hand, countries that

[1] For example, when Peru reported an outbreak of cholera in 1991, its South American neighbors imposed an immediate ban on Peruvian food products. The subsequent loss of $790 million in food sales and tourism revenues far exceeded the domestic health and productivity costs of the epidemic. As the Peruvian Minister of Health noted, "...nothing compares to the loss of markets [other countries] took away from us in a difficult time" (Panisset 2000, p. 150).

report an outbreak may obtain international medical assistance from WHO. Such medical assistance is typically offered with two objectives in mind - one humanitarian and other to prevent the outbreak from developing into a full-blown epidemic that could spread globally. Incentives to report an outbreak, however, are only half the story. A country must detect a disease in order to report its outbreak and it can influence the probability of detection by its investment in surveillance. The greater the return to reporting an outbreak, the greater the return to detecting the outbreak in the first place. We present a simple game-theoretic model to capture these basic dynamics.

We then explore certain extensions to deepen our understanding of surveillance and reporting incentives. First, we observe that trading partners often sanction countries even before the latter reveal an outbreak. Our analysis suggests that these "preemptive" sanctions are based on fears that a country will not reliably detect and report a disease outbreak. We find that these preemptive sanctions actually induce greater reporting because they reduce the relative cost of *ex post* sanctions and thus reporting.

Second, an important tool that international authorities have to influence surveillance and reporting is the quality of diagnostic technologies to identify outbreaks. The conventional view at agencies such as WHO and the U.S. Center for Disease Control and Prevention (CDC) is that better diagnostic technology – defined as an improvement in the sensitivity or specificity of testing – improves the ability to prevent or control epidemics. Improvements in testing technology are useful, however, only if countries are willing to use them and share the results. We find that improved technology actually reduces countries' own investments in surveillance and may also reduce reporting of outbreaks. Better technology improves the predictive value of tests, i.e., the probability that there is an outbreak (no outbreak) when one observes a positive (negative) test. But increasing the informativeness of a report causes trading partners to increase ex post sanctions following a report in order to limit the spread of any subsequent epidemic. It also causes trading partners to reduce preemptive sanctions when the country does not report. This reorientation of sanctions increases the relative cost of reporting. Because surveillance is less important if a country has decided not to report, surveillance will also fall. The overall effect may actually be to increase the expected loss of life from epidemics!

Third, an alternative source of information about disease outbreaks is rumors and improving the quality of rumor surveillance is another instrument that international authorities have to acquire better information about disease outbreaks. Although WHO actively monitors rumors (Samaan et al. 2005),[2] the public health community has criticized this so-called "rumor surveillance" because it is prone to errors, specifically false positives (Harris 2006). Extending the logic from our analysis of detection technology, we demonstrate, for example, that improving the specificity of rumors reduces investment in surveillance and might also discourage reporting and increase loss of life. The logic is similar to why improving technology may be harmful, with one exception. Whereas improving diagnostic technology reduces preemptive sanctions, improving the specificity of rumors increases preemptive sanctions when a country does not observe a positive test result but rumors indicate an outbreak. A practical implication is that reducing false positive rumors may be relatively less harmful to epidemic control than reducing false positives in testing technology.

Although this paper focuses on the problem of surveiling and reporting disease outbreaks, the structure of this problem is similar to that of many others encountered in economics. The structure involves one agent with multiple principals. The principals have overlapping if not identical interests, which include encouraging the agent to acquire and report information about his activities. The difficulty is that the principals control different levers and cannot coordinate their actions. Other problems that share this structure include incentives for: hospitals to report infections to public health authorities and patients; individuals to test themselves for STDs and report results to public health authorities and sexual partners; schools to

[2] But for rumor surveillance (i.e information flowing through informal networks of scientists and public health professionals), the international community would not have learnt of the SARS outbreak in China. Rumor surveillance is also used by WHO and the public health community for more routine tasks such as acquiring information on malaria epidemics.

identify and report poor teaching to the government and parents; cities to identify and report crime rates to national authorities and potential residents, tourist or businesses; companies to detect and report product defects, crimes by employees, and bad business investments to the government and to consumers or investors; and researchers to identify and report flaws in their analysis to journals and readers. It may be helpful to observe two additional features common to both the disease outbreak problem and the examples above. The principals in each case cannot coordinate because one of them is dispersed (e.g., trading partners, sexual partners, parents, consumers, etc.) and the only lever this dispersed principal can employ is a refusal to deal (a stick rather than a carrot). These features are relevant, though not essential, to the lesson we draw.

With respect to the set of problems that have the structure just described, the general question we examine is the effect of signal quality on information acquisition and revelation by agents. This framing highlights two literatures to which this paper relates. The first is the literature on common agency (see, e.g., Bernheim and Whinston 1986 and surveys by Dixit 1996 and Tirole 2001). The central distinction between this literature and the present paper is that the canonical common agency problem has multiple principals with different objectives. This is what generates an additional inefficiencies beyond the standard one principal-one agent problem. In this paper, however, we examine the case where multiple principals have the same objectives. Here inefficiency is generated by the inability of principals to coordinate their actions and thus free-riding amongst them. The results are analogous to those in Khalil et al. (2007), which examines a common agency problem where, although principals have differing objectives, each can monitor the agent in a manner that benefits other principals. This encourages free-riding and insufficient monitoring by principals.

The second literature to which this paper relates is that on incentives for information acquisition by agents. This literature has three distinct strands: auction design when the auctioneer wants bidders to invest in discovering their valuations (see the survey by Bergemann and Valimaki 2006), contract design when the principal wants the agent not only to exert effort but also to gather information (see, e.g., Prendergast 1993, Lewis and Sappington 1997, Cremer et al. 1998, Ewerhart and Schmitz 2000), and the design of legal rules to encourage sellers to test for product safety (Matthews and Postlewaite 1985; Shavell 1994; Arlen 1994; Arlen and Kraakman 1994). The central distinction between this literature and the present paper is that, with perhaps one exception, the former focuses on the case of one principal rather than two.[3] When there is only one principal, improvements in signal quality typically increase the amount of information supplied. Any disincentive effects that they may have on search or reporting by agents can typically be offset by compensating agents, through *ex ante* transfers, to offset the expected *ex post* costs of employing better signals. Where the principal lacks the ability to make such transfers, improvements in signal quality can reduce the amount of information produced.[4] This problem gets worse when there are multiple principals. Not only does free riding discourage *ex ante* transfers, the principals' inability to coordinate means that *ex post* costs to the agent of employing the better signals rise. In the context of disease outbreaks, trading partners will be even less willing to deal following disclosure of bad information.

The next section presents a simple game-theoretic model to illustrate the conflicting incentives to surveil and report disease outbreaks. Section 4 examines false negative test results and the role of preemptive sanctions. Section 5 introduces false positives into the analysis and explores the behavioral response to improvements in testing technology. Section 6 considers the effect of rumors on surveillance and reporting.

[3]Another distinction is that in this paper neither principal has the ability uniquely to reward or punish information acquisition and disclosure, a solution frequently suggested in the law and economics literature (see Arlen and Kraakman 1994 in the case of information acquisition and Kaplow and Shavell 1994 in the case of disclosure), either because of a budget constraint on the principal or limited liability of the agent. Indeed, it will become clear that even if the principals were not constrained in this manner, free riding problems discourage either principal from pursuing an optimal strategy from the one-principal case.

[4]The effect is analogous to, e.g., laws mandating disclosure of product defects, which may discourage companies from investigating potential defects in the first place (Polinsky and Shavell 2006).

3 Basic model

Consider a game with one agent - a "source" country - and two principals - WHO and a group of the country's trading partners. The source country has a small, exogenous probability of experiencing a disease outbreak. An outbreak is defined as a geographically localized infection affecting a very small number of people. The challenge is to prevent the outbreak from becoming a full-blown epidemic in the source country. An epidemic is a nation-wide infection that kills a large number of the country's residents. It may also spread internationally and become a pandemic that kills residents of the countries' trading partners. The source country must decide how much to invest in surveillance and, if it discovers an outbreak, whether or not to report this to WHO and its trading partners. WHO, in turn, must decide how much to subsidize surveillance and how much medical assistance to provide the country to help it control a reported outbreak.[5] Importantly, WHO cannot impose punitive sanctions on the country following an outbreak because it does not have the legal authority or power to do so. Trading partners, in contrast, may impose sanctions when a country reports evidence of an outbreak in order to reduce the risk that the epidemic reaches their borders (see, e.g., Brownstein et al. 2006). But they do not have meaningful medical assistance to provide after an outbreak, perhaps because of collective action problems. (We also assume that neither WHO nor trading partners can impose sanctions following a full epidemic either because it would not be politically palatable to kick a country when it is down or because the country is, in effect, limitedly liable because it has already suffered a large loss of life.)

The country's probability of an outbreak, its investment in surveillance, and the outcome of its surveillance are private knowledge. For now we assume the country cannot credibly reveal its probability of an outbreak, but can credibly reveal a positive test result. Although we only analyze a game involving one source country, we

[5] This medical assistance supplements the standard humanitarian assistance that all countries in distress typically receive. We shall ignore this technical detail to keep the model as simple as possible.

assume that WHO and trading partners know the distribution of outbreak probabilities across all possible source countries. All WHO and trading partner actions are observable.

The timing of the game is as follows:

1. WHO offers the country a surveillance subsidy t. The country determines its own investment x in surveillance.

2. The country suffers an outbreak with probability $p_0 > 0$. Country detects the outbreak with probability $q(x,t) > 0$ where q is increasing but concave in its arguments.

3. The country decides whether to report a positive test result to WHO.

4. If the country reports, WHO may provide medical assistance, c, to control the outbreak and, simultaneously, trading partners may impose sanctions S. If there is no report, there is no assistance or sanction.[6]

5. The outbreak becomes a full-blown epidemic with probability $p_1(c)$, where $p_1' < 0$, $p_1'' > 0$. The epidemic kills $k(S)y$ people, y in the source country and $[k(S) - 1]\, y > 0$ residents of its trading partners. Because sanction limit the spread of disease, $k' < 0$, $k'' > 0$.

It is assumed that the functions q, p_1, and k are common knowledge and obey the usual regularity conditions. We ignore time discounting because it does not make the model any more informative.

Since a central focus of this paper is the effect of information quality on surveillance and reporting, we define Λ (Γ) as the unconditional probability of a positive (negative) test result, and λ (γ) as the probability of an outbreak (no outbreak) given a positive (negative) test result. The term λ (γ) is also known as the positive

[6] We relax the assumption that trading partners may not impose sanctions without a positive report in the next section. We always assume that WHO provides no medical assistance without evidence of a positive test result. The reason is that, whereas a positive test result reveals who exactly has the infection and ought to be treated, a negative test result does not. Therefore, even if the negative test result is false, WHO medical assistance to prevent spread of the local infection is of no use, i.e., $p_1'(c \mid \text{negative test}) = 0$.

Test result, probability	Report result was positive	Payoff
Positive, Λ	No	$-x-\lambda p_1(0)\,y$
	Yes	$-x-\lambda p_1(c)\,y-S$
Negative, Γ	No	$-x-(1-\gamma)\,p_1(0)\,y$

Table 1: Country's payoffs in basic model.

(negative) predictive value of diagnostic technology. For simplicity, the basic model assumes that surveillance is subject to false negatives (with probability $1-q$), but not false positives. This implies that $\Lambda = p_0 q$ and $\Gamma = p_0(1-q)+(1-p_0) = 1-p_0 q$. Moreover, $\lambda = 1$ and $\gamma = (1-p_0)/\Gamma$.

The source country's payoffs are given in Table 1. Because the country only observes surveillance test results, not an outbreak, test results are what determine payoffs. Because investment x in surveillance occurs before an outbreak, that cost is borne regardless of whether or not there is an outbreak. If a country observes a positive test result, the probability there is actually an outbreak is λ. Since we are assuming, for now, that there are no false positives, $\lambda = 1$. If the country does not report it has observed a positive test result, it faces a higher probability $p_1(0)$ that the outbreak will develop into an epidemic. If it does report, it will face sanctions S, but with the help of WHO medical assistance c, a smaller risk $p_1(c)$ of an epidemic.[7] If the country observes a negative test result, it will not report that it has observed a positive test result. There is no value to WHO medical assistance since medical assistance is only useful if the country can pinpoint the outbreak (see note 6). Moreover, reporting brings the likelihood of trade sanctions. Therefore, we shall ignore the option of reporting despite a negative test result. Even though the country does not report, there is a chance $(1-\gamma)$ that the negative test result was incorrect and there is an outbreak. Because the country receives no medical assistance, the probability of an epidemic is $p_1(0)$.

[7]It might seem odd that the country is assumed to have resources for surveillance but not to control an outbreak. Surveillance typically costs less resources than outbreak containment. Moreover, relaxing this assumption will not alter the important dynamics. A country will be willing to surveil even in a no-report equilibrium, though that is not the equilibrium on which we focus. If the country's and WHO assistance are substitutes, the latter will crowd out the former. This moral hazard will reduce the second-best amount of assistance the WHO will provide upon the report of a positive test result unless the WHO seeks to allocate more resources to control than the country has.

WHO's objective is to minimize the consequences of an epidemic and its financial costs. WHO's objective may be written:

$$\max_{t,c} -t - E\left[\Lambda\left\{\lambda p_1(c)\,k(S)\,y + c\right\}|\text{report}\right] \qquad (1)$$
$$-E\left[\Lambda\lambda p_1(0)\,k(0)\,y|\text{not report}\right] - E\left[\Gamma(1-\gamma)\,p_1(0)\,k(0)\,y\right]$$

where, for ease of reading we have suppressed the reliance of $(\Lambda, \Gamma, \lambda, \gamma)$ on p_0 and $q(x,t)$ and expectations are taken with respect to $f(p_0)$, the distribution of outbreak probabilities across countries. The first term in the maximand is the surveillance subsidy, a cost regardless of whether a country reports and whether there is an outbreak. The second term reflects the average loss among countries that suffer an epidemic, observe a positive test result and report. WHO provides aid, which reduces the risk of an epidemic. A national epidemic can spread and become a worldwide pandemic. Whereas the country only cares about the deaths y of its residents, WHO cares about all deaths $k(S)y$ worldwide. The third term reflects the average loss among countries that experience an epidemic, observe a positive test result, but choose not to report. The fourth term reflects the average loss among countries that experience an epidemic but observe a false negative test result. The loss is the same these last two cases. There is a higher probability that an outbreak will become an epidemic because WHO provides no aid, and a higher probability that an epidemic will spread internationally because there are no trading partner sanctions.

WHO and trading partners cannot coordinate so we discuss trading partner payoffs from sanctions separately. Countries trade because it creates surplus that is split among them. For simplicity we assume the surplus is $2S$, which is split equally. We treat sanctions as a refusals to deal and thus quantify them by the implied loss of surplus from trade. The benefit of sanctions, however, is that they reduce the risk that an epidemic will spread because trade and tourism are an importance vehicle by which diseases move across boundaries. Assuming the country reports positive test results and given that trading partners can only sanction when a country reports, the trading partners' objective is

$$\max_{S} -E\left[\Lambda\left\{\lambda p_1(c)\left\langle k(S)-1\right\rangle y+S\right\}|\text{report}\right] \tag{2}$$
$$-E\left[\Lambda\left\{\lambda p_1(0)\left\langle k(0)-1\right\rangle y\right\}|\text{not report}\right]-E\left[\Gamma\left\{(1-\gamma)\,p_1(0)\left\langle k(0)-1\right\rangle y\right\}\right]$$

The first term captures the cases where a country experiences an epidemic, observes a positive test, and reports. Sanctions only reduce death if there is an epidemic, i.e., with probability $p_1(c)$. We subtract 1 from the multiplier k because trading partners do not internalize the loss of life in the source country. The second term captures the case where there is an outbreak and positive test result, but no reporting, and the third term captures the case where there is an outbreak but a negative test result.

3.1 First Best

The first-best case is one in which the country, WHO and trading partners coordinate their response. The probability of an outbreak and all choices are common knowledge. No one observes the outbreak, but everyone observes test results. For purposes of exposition, we maintain the assumption that trading partners can only sanction when there is a positive test result. (We shall relax this constraint in the next section.) The social welfare function from an ex ante perspective is

$$\max_{t,x,S,c} -x-t-\Lambda\left[\lambda p_1(c)k(S)y+c+2S\right]-\Gamma\left[(1-\gamma)\,p_1(0)k(0)y\right] \tag{3}$$

The key features here are that the social planner considers all financial costs (from country investment in surveillance and from WHO subsidies), internalizes the costs of sanctions on both the country and trading partners, and internalizes the worldwide risks from an epidemic. Define (c^{FB}, S^{FB}) as the solutions to the optimality conditions $p_1'(c^{FB}) = -1/k(S^{FB})y$ and $k'(S^{FB}) = -2/p_1(c^{FB})y$, and (t^{FB}, x^{FB}) as the solutions to the optimality conditions

$$q_i\left(x^{FB}, t^{FB}\right) = \frac{1}{p_0\left\{\left[p_1(0)k(0) - p_1(c^{FB})k(S^{FB})\right]y - c^{FB} - 2S^{FB}\right\}} \tag{4}$$

for $i = x, t$.

Proposition 1 *Assume (A1)* $q_{xx}q_{tt} > q_{xt}^2$ *at* (x^{FB}, t^{FB}) *and (A2)* $p_1''k''/p_1'k' > p_1'k'/p_1k$ *at* (x^{FB}, t^{FB})*. Then* $(x^{FB}, t^{FB}, c^{FB}, S^{FB})$ *maximize the social welfare function.*

Proof. The definitions of (c^{FB}, S^{FB}) and the convexity of $p_1(c)$ and $k(S)$ imply that $\{p_1(0)k(0) - p_1(c^{FB})k(S^{FB})\}y - c^{FB} - 2S^{FB} > 0$. In addition, A1 - A2 are necessary and sufficient conditions for the Hessian of the social welfare function to be negative definite. ■

The first assumption required for an internal maximum is that the interaction q_{xt} between country and WHO investments in surveillance is not too large. The second assumption is that WHO medical assistance and trading partner sanctions have sufficiently diminishing returns at containing an outbreak and epidemic, respectively. This assumption is satisfied, for example, if both $p_1(c)$ and $k(S)$ are log-convex.

3.2 Second Best

In the second-best case, the country, its trading partners and WHO play a non-cooperative game. In a subgame perfect Nash equilibrium, trading partners' sanctions and WHO medical assistance upon report of a positive test result satisfy $k'(S^{SB}) = -1/p_1(c^{SB})y$ and $p_l'(c^{SB}) = -1/k(S^{SB})y$, respectively.

A country will report a positive test result so long as sanctions are sufficiently weak and/or medical assistance is sufficiently generous:

$$S^{SB} \leq \left[p_1\left(0\right) - p_1\left(c^{SB}\right)\right]y = \Delta p_1\left(0, c^{SB}\right)y \tag{5}$$

Notice, first, that this decision does not depend on the probability of an outbreak. Since this is the only source of heterogeneity in our model, either all countries in the world will report or all countries will not report. Since the non-reporting case is not very interesting, we shall give more attention to the all-reporting case. Second, WHO cannot incent the country to report with medical assistance or surveillance subsidies. WHO medical assistance has limited strategic value in a one-play, sequential game because threats to withhold aid or lower sanctions are not subgame perfect and thus non-credible. (The same is true for trading partner sanctions.) Surveillance subsidies have little power because the reporting decision is made only after surveillance has done its job.

If the country would report a positive test result, it will set its investment in surveillance such that

$$q_x\left(x^{SB}, t^{SB}\right) = \frac{1}{p_0\left\{\Delta p_1\left(0, c^{SB}\right) y - S^{SB}\right\}} > 0 \tag{6}$$

Because q is concave, the greater the net benefits of reporting, the more the country will invest in surveillance. If all countries report positive test results, WHO will offer a surveillance subsidy that satisfies

$$E\left[p_0 q_t\left(x^{SB}\left(p_0\right), t^{SB}\right)\right] = \frac{1}{\left[p_1(0)k(0) - p_1(c^{SB})k(S^{SB})\right] y - c^{SB}} \tag{7}$$

WHO's subsidy is keyed to its gain from detection, including lives saved not just in the country but worldwide. Of course it discounts this value appropriately by the cost of having to provide medical care and the expected probability that there will be an outbreak. If no countries report, then neither the countries nor WHO promote surveillance because there is no return to doing so. Recall that countries are assumed to have no medical resources to contain an outbreak even if they find one.

There are three differences between the first best problem and the non-cooperative game. First, neither the country nor trading partners internalize the cost of sanctions on one another in the non-cooperative game. Second, the country does not internalize the cost of an epidemic on trading partners. Third, countries might not report in the non-cooperative game. In general, one cannot compare the first and second best outcomes because a different solution concept is employed in the social planner problem and in non-cooperative game. But if one makes the assumptions required to ensure that the social planner problem is concave and ignores private information, however, one can generate convergence between the solutions to the two problems and examine behavior along the path of convergence. The following proposition reports the results.

Proposition 2 *Suppose assumptions (A1) and (A2) hold and all countries are in a reporting equilibrium in the non-cooperative game. If the country and trading partners internalize more of the loss of surplus from sanctions, trading partner sanctions will fall, WHO medical assistance will rise, and WHO surveillance subsidies will fall. The expected loss of life conditional on a positive test result will also rise. The effect on country investment in surveillance is ambiguous. If the country internalizes more of the foreign loss of life due to an epidemic, its investment in surveillance will rise.*

Proof. See appendix. ■

The failure to internalize the country's loss of surplus from sanctions causes trading partners to enact higher sanctions than are optimal following the report of an outbreak. This in turn lowers the value of WHO's medical assistance in containing the outbreak and thus the amount of that assistance. Surprisingly, the balance of effects actually lowers the expected loss of life following the report of a positive test result! It is uncertain whether there will be more or less surveillance in the second best. Because failure to internalize the cost of sanctions to the source country reduces expected loss of life following a report, there is actually greater return to and thus a larger amount of WHO surveillance subsidies in the second best. The effect on the country's investment in surveillance is ambiguous, an important reason being that we have not made any assumptions about whether country and WHO contributions to surveillance are substitutes or complements, i.e., the sign of q_{xt}. Even ignoring this ambiguity, failure to internalize the cost of an epidemic on trading partners has the counterproductive effect of lowering the value and thus level of country investment in surveillance.

Reporting in the first and second best cases are not comparable since there we assume no private information in the first best. It is enlightening, however, to note the potential causes of non-reporting in the second best. The second best reporting condition (5) is made more strict – implying "less" reporting – because reporting has both a higher cost and lower gain when players fail to internalize the costs of their actions. The cost is higher because trading partners impose higher sanctions when they fail to internalize the full cost of sanctions. The gain is lower because the country fails to internalize the cost of an epidemic on trading partners, and thus the full gain from better control of an outbreak when it is reported. The gain is lowered further still because WHO provides less care when trading partner sanctions are higher. These bad effects are partly offset by two facts. One is that higher sanctions from trading partners reduce the risk that contagion will spread to other countries, increasing the gain from sanctions. The other is that the country's failure to internalize the full cost of sanctions actually lowers the direct cost of reporting.

4 False negatives and preemptive sanctions

In this section we relax the assumption that trading partners cannot sanction unless the country reports an outbreak. We demonstrate that, because the diagnostic technology is subject to false negatives, it is rational for trading partners to sanction the country even when it does not report a positive test result. We label such sanctions as preemptive or ex ante sanctions because they occur even before the country reports an outbreak and give real-world examples of these sanctions. Finally, we show that preemptive sanctions, in turn, have two beneficial effects. First, they reduce the disincentive effects that ex post sanctions have on reporting. Second, preemptive sanctions offer WHO a new strategy with which to generate an equilibrium with full reporting by all countries, i.e., the unravelling result from Grossman (1981) and Milgrom (1981). Specifically, if by offering to audit diagnostic test results the WHO can discover a country's private probability of an outbreak, then the WHO can induce all countries to report their test results.

Preemptive sanctions R differ from ex post sanctions S in that trading partners enact them only in the states where there is a negative test result or there is a positive test result that the country does not report. We assume that preemptive sanctions are as effective as ex post sanctions at preventing the spread of an epidemic from the country to trading partners. The loss of surplus due to ex post sanctions is $2R$, split equally between the country and the trading partners. Whereas the costs of preemptive sanctions are borne whenever the country is a reporting equilibrium but observes a negative test result or the country is in a no-reporting equilibrium, the benefit from preemptive sanctions accrue only when, in addition, there is an outbreak. This implies the trading partners' objective is

$$\begin{aligned}&\max_{S,R} -E\left[\Lambda\left\{\lambda p_1(c)\left[k(S)-1\right]y+S\right\}|\text{report}\right] \\ &-E\left[\Lambda\left\{\lambda p_1(0)\left[k(R)-1\right]y+R\right\}|\text{not report}\right] \\ &-E\left[\Gamma\left\{(1-\gamma)\,p_1(0)\left[k(R)-1\right]y+R\right\}\right]\end{aligned} \tag{8}$$

We remind readers that, for now, we are assuming there are no false positive, so $\lambda = 1$ for all countries.

Trading partners' second best choice of preemptive sanctions depend on which countries report. The reporting condition with preemptive sanctions, like that without such sanctions, does not depend on a country's underlying probability of an outbreak:

$$S^{SB} - R^{SB} \leq \Delta p_1\left(0, c^{SB}\right) y \tag{9}$$

Since that probability is the only source of heterogeneity in our model, either all countries report or all countries do not report. If all countries report, then trading partners set preemptive sanctions such that

$$k'(R^{SB}) = \frac{E\left[\Gamma\right]}{E\left[\Gamma\left(1-\gamma\right)\right]}\left[\frac{-1}{p_1\left(0\right)y}\right] \tag{10}$$

where for readability we ignore the SB-superscript on functions of $q\left(x^{SB}, t^{SB}\right)$. If no countries report, then preemptive sanctions satisfy $k'\left(R^{SB}\right) = -1/E\left[p_0\right] p_1(0)\, y$. Again, because the none-reporting case is less interesting, we devote more attention to the all-reporting case. Comparing (10) to the optimality condition for ex post sanctions, $k'\left(S^{SB}\right) = -1/p_1\left(c^{SB}\right) y$, it should be evident that preemptive sanctions are lower than ex post sanctions so long as the probability of an outbreak given a negative test result is less than the relative odds of an epidemic when WHO provides medical assistance

$$\frac{E\left[\Gamma(1-\gamma)\right]}{E\left[\Gamma\right]} < \frac{p_1\left(c^{SB}\right)}{p_1(0)} \tag{11}$$

The smaller the average likelihood of a false negative, the less the containment benefit of preemptive sanctions. The greater the containment benefit of WHO assistance, the less the need for containment with ex post sanctions. The condition in (11) is very likely to hold because diagnostic tests are typically very sensitivity and ex post medical containment is imperfect.

The country's investment in surveillance will now account for the fact that reporting has the additional benefit of avoiding preemptive sanctions:

$$q_x\left(x^{SB}, t^{SB}\right) = \frac{1}{p_0\left\{\Delta p_1\left(0, c^{SB}\right) y - S^{SB} + R^{SB}\right\}} > 0 \tag{12}$$

WHO subsidies will also account for preemptive sanctions, which have two effects. First, because preemptive sanctions control epidemics, they reduce the cost of failed surveillance. This reduces the return to subsidies. Second, because preemptive sanctions depend on total surveillance, which in turn depend on WHO subsidies known to trading partners, WHO knows its subsidies will reduce preemptive sanctions:

$$\frac{\partial R^{SB}}{\partial t} = \frac{E\left[p_0 q_t^{SB}\right]}{E\left[\Gamma(1-\gamma)\right]} \frac{p_1(0)\, k'\left(R^{SB}\right) y + 1}{p_1(0)\, k''\left(R^{SB}\right) y} < 0 \tag{13}$$

This will increase the return to subsidies. Together these effects imply that WHO sets its subsidies such that

$$E\left[p_0 q_t\left(x^{SB}\left(p_0\right), t^{SB}\right)\right] = \frac{1 - E\left[\Gamma\right]\frac{\partial R}{\partial t}}{\left[p_1(0)k(R^{SB}) - p_1(c^{SB})k(S^{SB})\right] y - c^{SB}}$$

Preemptive sanctions change slightly our comparison of the first best and second best result from the previous section. Because of the strategic interaction between WHO subsidies and preemptive sanctions highlighted in (13), it is unclear whether making trading partners internalize a greater portion of the social cost of their preemptive sanctions causes WHO to raise or lower its surveillance subsidies or trading partners to raise or lower their preemptive sanctions.

More interesting is the comparison of the second best result without preemptive sanctions and the second best with preemptive sanctions. Our analysis is summarized in the following proposition.

Proposition 3 *Suppose that all countries are in a reporting-equilibrium and that (A3)* (p_1, k) *are both log-convex or log-concave. Then preemptive sanctions have no effect on WHO medical assistance and ex post sanctions, but they do decrease WHO subsidies. If* x *and* t *are weak substitutes so that* $q_{xt} \leq 0$*, then preemptive sanctions raise country investment in surveillance.*

Proof. See appendix. ■

Assumption (A3) may not be necessary, but it is sufficient to obtain the clean results of Proposition 3. It is not overly restrictive, mainly ruling the case where p_1 and k are exactly exponential, in which case the comparative statics are not identified.

Preemptive sanctions have two effects. Preemptive sanctions help contain an epidemic even if it is not discovered and reported. Therefore, they reduce the return to WHO subsidies for surveillance. Assuming WHO subsidies and a country's own investment in surveillance are not complements, own investment rises because the return to surveillance is proportional to the return to reporting and – as we shall see – preemptives increase the relative return to reporting.

Suppose the reporting condition (9) does not hold and all countries are in a not-reporting equilibrium. Although it is not met, the reporting condition can be rewritten as a cutoff for the lives lost in an epidemic: a country will report only if $y > \left(S^{SB} - R^{SB}\right)/\Delta p_1\left(0, c^{SB}\right) = W$. It is immediately obvious that increasing preemptive sanctions reduces the cutoff for reporting, decreasing the number of cases – as indexed by y – where no countries report:

$$\frac{\partial W}{\partial R} = \frac{-1}{\Delta p_1\left(0, c^{SB}\right)} < 0$$

The intuition is that preemptive sanctions punish countries even when they do not report. Therefore, they reduce the relative cost of reporting.

There are many recent examples of preemptive sanctions. To identify such sanctions, note that human infections that have animal originals typically take the following path: (i) no animal infection, (ii) animal infection, (iii) animal-to-animal transmission, (iv) animal-to-human transmission, and (v) human-to human transmission. At each of these junctures, trading partners have the opportunity to sanction the country. Because it is human-to-human transmission that might be contained with WHO medical assistance and that poses the most serious risk of an epidemic, sanctions that occur after stage (iv) are ex post sanctions. Earlier sanctions are preemptive sanctions. Table 2 gives examples of preemptive sanctions. They are grouped according to whether they in stage (i) or in stage (ii)/(iii). All the sanctions occurred before any animal-to-human transmission, let alone human-to-human transmission.

Preemptive sanctions do not simply promote reporting in the context of the game set forth in Section 3, they also offer WHO a new policy instrument – an audit of a country's surveillance – that can generate an equilibrium with full information disclosure regardless of whether the reporting condition (9) is satisfied. The key to this result is that a WHO audit must be able to credibly reveal to trading partners that a country's probability of suffering an outbreak. (Countries cannot signal safety on their own because it is very easy to fake negative test results.) The logic straightforward. In the absence of credible information on the outbreak risk in a country, trading partners set preemptive sanctions based on the average risk of an

Date	Disease/Location	Sanction
Sanctions imposed before animal outbreaks (stage i)		
2005	HPAI/not specific	Vietnam bans imports of poultry from 16 countries
2006	HPAI/France	Poultry consumption fell 20% in France before HPAI discovered
2006	HPAI/Bulgaria	Poultry sales fell 60% in Bulgaria before HPAI discovered in swans
Sanctions imposed after animal outbreak, before human outbreak (stages ii or iii)		
1997	HPAI/Hong Kong	Hong Kong kills 1.5 mil. chickens
2001	FMD/UK	Cost UK tourism and beef industries £3 billion even before human casualties
2003	AI/ US	US poultry exports may have fallen 3% (Blayney 2005)
2003	BSE/US	US beef exports fell 80% without a single human infection (Blayney 2005)
2003-2005	HPAI/SE Asia	SE Asian economies loss $12 bil. in output (Thailand alone $1 bil., Vietnam up to 1.8% GDP; outside SE Asia, poultry prices up 20%, volume down 8%)
2005	HPAI/not specific	US ban poultry imports from all countries reporting animal outbreaks (WSJ Nov. 21, 2005)
2006	HPAI/Italy	Poultry consumption fell 70% in Italy
Notes. HPAI = highly pathogenic avian influenza, AI = avian influenza (not highly pathogenic), FMD = foot and mouth disease, BSE = mad cow disease.		

Table 2: Examples of preemptive sanctions.

outbreak. If trading partners knew that a country was safer than average, they would lower their preemptive sanctions against that country because there would be less risk of an outbreak in the absence of reporting. Thus safer countries will prefer to be audited to convince trading partners to lower their preemptive sanctions against them. Trading partners respond by adjusting upwards their expectations about the average risk of outbreak in non-audited countries. Again non-audited countries with lower-than-average risk will seek WHO audits. And so on. Under certain conditions, the process will continue until all but the most risky country seek WHO audits. An equilibrium with unraveling is illustrated in Appendix B.

5 False positives and effect of testing technology

The public health community places great emphasis on the technological accuracy of diagnostic testing for disease. For example, WHO has stated that one of the central goals of that organization and of the Food and Agriculture Organization of the United Nations is to "facilitate, through their research networks, the rapid development of new methods for detecting the [avian influenza] virus in environmental samples" (WHO 2005). Julie Gerberding, the director of the U.S. Centers for Disease Control & Prevention, has stated that transfer of diagnostic technologies is a central goal in promoting surveillance of avian influenza (Gerberding 2005).[8]

What's more, this emphasis on the technology has been biased in favor of improving the sensitivity of diagnostic technology, i.e., on the probability that testing technology detects disease in an infected patient. For example, both WHO Manual on Animal Influenza Detection and Surveillance (2002) and the U.S. president's National Strategy for a Pandemic Influenza (2005) repeatedly stress the importance of improving the sensitivity of tests but not once mention the specificity of tests, i.e., the probability that a test detects no disease in an non-infected person. Their logic

[8] All quarters have lauded, for example, the introduction of the MChip (a new technology to detect avian flu) as a big step forward in global surveillance efforts and efforts to reduce the human impact of that disease (Townsend et al. 2006; DrugResearcher.com 2006). Indeed, the development of that technology was funded directly by the U.S. National Institutes for Health (Fox 2006). Even the FDA has expedited review and approval of new diagnostic technologies for avian flu to aid the cause (U.S. Department of Health and Human Services 2006).

is that one cannot stop an epidemic if one does not detect an outbreak. Increasing test sensitivity and its corollary – reducing false negatives – ensure that the infected do not go without treatment and spread contagion.

In this section we question both the great value placed on improving technology and the preference for sensitivity over specificity. Specifically, we show that improving technology may actually decrease reporting because, for example, it increases the informativeness of reporting and thus the sanctions that trading partners impose on countries that report. The end result may even be a higher expected loss of life with better technology. We stress that this is not a necessary result of technology, but rather a possible result. Even if we ignore it, however, we find that specificity may be as important to reporting incentives as sensitivity. The reason is that reducing false positives reduces the frequency of cases where a country reports an outbreak though it has not suffered one. These cases discourage reporting because the country suffers ex post sanctions with offsetting benefits from WHO medical assistance since there to outbreak to control.

In order to illustrate these points, let q be (as before) sensitivity, i.e., the probability of a positive test result given an outbreak, and let r be specificity, i.e., the probability of a negative test result given no outbreak. This implies that the probabilities of technological false negatives and false positives are $1 - q$ and $1 - r$, respectively.[9] Further,

$$\begin{aligned} \Lambda &= \Pr(\text{positive test}) = p_0 q + (1 - p_0)(1 - r) \\ \Gamma &= \Pr(\text{negative test}) = p_0(1 - q) + (1 - p_0) r \end{aligned}$$

[9] Repeated testing will not always overcome false positives. First, early in their development, diagnostic tests might employ indicators for multiple ailments, including the disease being targeted. This will imply strong positive correlation across test results for a patient who has one of those ailments, but not the disease. Second, early in an outbreak, there may be a great deal of confusion. This confusion can lead to false positives that are not reversed for some time (see, e.g., Zamiska Oct. 18, 2005). Third, false positives may trigger sanctions before a second test is conducted (see, e.g., Canadien Press Sept. 9, 2003). Indeed, they may still trigger greater preemptive sanctions in the future. Trading partners might rationally believe there is a greater chance of an outbreak despite a second negative test result because it is possible the second test result was a false negative.

$$\lambda = \Pr(\text{outbreak} \mid \text{positive test}) = \frac{p_0 q}{p_0 q + (1-p_0)(1-r)} < 1 \tag{14}$$

$$\gamma = \Pr(\text{no outbreak} \mid \text{negative test}) = \frac{(1-p_0)r}{p_0(1-q) + (1-p_0)r} \tag{15}$$

Because of imperfect specificity, there is a higher probability of a negative test result, though that result has less predictive value, than in the basic model with perfect specificity.

In order to streamline the analysis, we shall ignore WHO subsidies for surveillance. We continue to assume that country can improve sensitivity by its investments x. In addition, it can improve specificity by investment z in, for example, repeat testing of positive results. In order to incorporate technology, we shall rewrite q and r as

$$q = \alpha q(x), \; r = \beta r(z)$$

where the functions (q, r) are increasing but concave and $\alpha, \beta > 0$ are technology parameters that increase the marginal productivity of investments in surveillance. but initially we take specificity to be exogenous. The country will report a positive test result if the payoff from reporting $(-\lambda p_1(c)\, y - S)$ is greater than the payoff from not reporting $(-\lambda p_1(0)\, y - R)$. Although sanctions are triggered based on the country's report, the probability of an epidemic depends on the predictive value of a positive test result, i.e., on the probability λ. The important difference from the case without false positives is that $\lambda < 1$. This implies that the reporting condition depends on the probability p_0 of an outbreak:

$$p_0 > \frac{\left(1-\beta r^{SB}\right)\left(S^{SB} - R^{SB}\right)}{\alpha q^{SB} \Delta p_1\left(0, c^{SB}\right) y + \left(1 - \beta r^{SB} - \alpha q^{SB}\right)\left(S^{SB} - R^{SB}\right)} = W \tag{16}$$

Because there is heterogeneity in this probability, there is now a possible equilibrium in which some countries report and others do not. Focusing on this more interesting case, the questions we would like to answer are: how does increasing either sensitivity or specificity alter surveillance and the reporting cutoff W, and what effect does this have on expected loss of life?

If a country is in a reporting equilibrium, its optimal investment in sensitivity and specificity satisfy

$$
\begin{aligned}
q_x\left(x^{SB}\right) &= \frac{1}{p_0\alpha\left[\Delta p_1\left(0, c^{SB}\right) - S^{SB} + R^{SB}\right]} \\
r_z\left(z^{SB}\right) &= \frac{1}{\left(1-p_0\right)\left[S^{SB} - R^{SB}\right]}
\end{aligned}
$$

Note that, whereas the return to sensitivity falls in the relative sanctions-related costs of reporting, the return to specificity rises in these costs. The reason is that greater sensitivity rules out false negatives and thereby moves outbreak states of the world from the non-reported to the reported set, and thus to higher relative sanctions. Greater specificity does the opposite, it shifts non-outbreak states from the reported set to the non-reported set, and thus away from higher relative sanctions. If a country is in a no report equilibrium, it will invest nothing in sensitivity or specificity because, in the absence of reporting, there are no returns to doing so. Because it is possible in equilibrium that some countries report while other simultaneously do not, trading partners must set ex post sanctions with an eye only toward reporting countries that observe a positive test result, and set preemptive sanctions with an eye both toward reporting countries that observe a negative test result and toward non-reporting countries. The optimality conditions for sanctions are therefore

$$
\begin{aligned}
k'\left(S^{SB}\right) &= \frac{E\left[\Lambda|\text{report}\right]}{E\left[\Lambda\lambda|\text{report}\right]}\left(\frac{-1}{p_1\left(c^{SB}\right)y}\right) \\
k'\left(R^{SB}\right) &= \frac{E\left[\Lambda|\text{not report}\right] + E\left[\Gamma\right]}{E\left[\Lambda\lambda|\text{not report}\right] + E\left[\Gamma\left(1-\gamma\right)\right]}\left(\frac{-1}{p_1\left(0\right)y}\right)
\end{aligned}
$$

where again for readability we leave out SB-superscripts on functions that depend on $q\left(x^{SB}\right)$ and $r\left(z^{SB}\right)$.[10] Finally, WHO only provides care only when a country

[10] It must be the case that ex post sanctions are greater than preemptive sanctions when a strict subset of countries report. If not we get a contradiction since the cutoff in (16) would be negative, suggesting all countries report. If all countries report, ex post sanctions are greater than preemptive sanctions only when

$$
\frac{E\left[\Lambda\right]}{E\left[\Lambda\lambda\right]}\frac{E\left[\Gamma\left(1-\gamma\right)\right]}{E\left[\Gamma\right]} = \frac{p\left(1-q\right)}{pq} < \frac{p_1\left(c^{SB}\right)}{p_1\left(0\right)}
$$

reports. But since not all may countries report in a non-zero reporting equilibrium, the optimality condition for medical aid is

$$p_1'(c) = \frac{E[\Lambda|\text{report}]}{E[\Lambda\lambda|\text{report}]}\left(\frac{-1}{k(S^{SB})\,y}\right)$$

The following propositions summarize each player's response to an increase in sensitivity and specificity.

Proposition 4 *An increase in either α or β reduces preemptive sanctions and increases a country's investment in specificity. If (A3) holds, then it also increases ex post sanctions and medical assistance. The effect on investment in sensitivity is ambiguous. If one further assumes, however, that (A4) the curvature of the functions p_1 and k satisfy $P < E[\lambda|\text{report}]\,k(S)\,K$ where P and K are the curvature parameters*

$$P = \left|\left(\frac{p_1''}{-p_1'}\right) - \left(\frac{-p_1'}{p_1}\right)\right|, \; K = \left|\left(\frac{k''}{-k'}\right) - \left(\frac{-k'}{k}\right)\right|$$

for all (c, S), then an increase in α or β reduces investment in sensitivity.

Proof. See appendix. ■

The key contribution of both increased sensitivity and increased specificity is greater positive (14) and negative (15) predictive value of test results. This in turn increases the return to medical assistance and ex post sanctions because any report is less likely to be a false alarm. Conversely, the return to preemptive sanctions falls because a negative test result – one of the two possible explanations for the absence of no report – is less likely to be incorrect and thus require precautionary actions. The net effect is to increase twice the relative sanctions-related cost of reporting. Because greater relative sanctions increase the return to specificity, investment in specificity rises. As for sensitivity, the net effect is ambiguous. The greater relative sanctions discourage investment, but greater medical assistance encourages investment. Under the technical conditions indicated, we can be sure the sanctions

This condition is roughly equal to the condition that $\left(1 - q^{SB}\right)/q^{SB} < p_1\left(c^{SB}\right)/p_1(0)$, i.e., that the relative odds of a false negative are less than the relative odds of an epidemic when WHO provides medical assistance.

effect outweighs the assistance effect.

In order to deduce the implication of Proposition 4 for reporting, take the derivative of the reporting cutoff W with respect to, say, sensitivity parameter α:

$$\begin{aligned}\frac{\partial W}{\partial r} = & \left[\frac{-W\left[\Delta p_1(0,c)-S+R\right]}{D}q(x)\right]+\left[\frac{W}{D}\alpha q(x)\,p_1'(c)\,y\right]\frac{\partial c}{\partial \alpha} \\ & +\left[\frac{-(1-W)\,\Delta S}{D}\beta r_z(z)\right]\frac{\partial z}{\partial \alpha}+\left[\frac{Wq+(1-W)(1-r)}{D}\left(\frac{\partial S}{\partial \alpha}-\frac{\partial R}{\partial \alpha}\right)\right] \\ & +\left[\frac{-W\left[\Delta p_1(0,c)-S+R\right]}{D}\alpha q_x(x)\right]\frac{\partial x}{\partial \alpha}\end{aligned}$$

where $D = \alpha q(x)\,\Delta p_1(0,c)\,y + [1-\beta r(z)-\alpha q(x)](S-R) > 0$ and we suppress SB-superscripts for ease of readability. On the one hand, greater specificity might increase reporting by lowering the reporting cutoff. The immediate benefit of sensitivity – captured in the first term – is to introduce reporting only to states where there is an outbreak for sure and therefore medical assistance has its greatest positive impact.[11] An indirect inducement to reporting – the second term – is that greater sensitivity increases WHO medical assistance, a benefit of reporting. Another indirect inducement – the third term – is that sensitivity causes the country to invest more in specificity, which in turn eliminates some situations where the country suffers ex post sanctions but obtains no benefit from WHO medical assistance. On the other hand, sensitivity can deter reporting by increasing the reporting cutoff. The most important disincentive – the fourth term – is that increasing specificity makes ex post sanction more effective and preemptive sanctions less necessary. Another possible disincentive – the fifth term – is that sensitivity might cause the country to reduce its investment in sensitivity, offsetting some of the immediate benefits of sensitivity in the first term.[12] The overall effect is uncertain, with the one certain culprit being the increase in relative sanctions. Given Proposition 4, an increase

[11] Note that the set of cases that satisfy the reporting condition $E[\Lambda\lambda|\text{report}]\,\Delta p_1(0,c)\,y > E[\Lambda|\text{report}](S-R)$ is a subset of the cases that satify the more lax condition $\Delta p_1(0,c)\,y > S-R$. Increased sensitivity simply increases $E[\Lambda\lambda|\text{report}]$ relative to $E[\Lambda|\text{report}]$ which expands the boundary of the reporting subset.

[12] The impact of technology on reporting is not identical to its impact on investment in sensitivity because the former is proportional to $\lambda\Delta p_1\left(0,c^{SB}\right)-S^{SB}+R^{SB}$ while latter is proportional to $\Delta p_1\left(0,c^{SB}\right)-S^{SB}+R^{SB}$. The reason is that sensitivity q has the same effect on the the probability of a positive test (Λ) as on the joint probability of a positive test and an outbreak ($\Lambda\lambda$).

in the specificity parameter β has similar effects on reporting with one primary exception. The immediate benefit of sensitivity is $-(1-W)\Delta S\beta r(z)/D<0$.

Just as with reporting, it is not possible to sign the effect of technology on expected loss of life among all countries,

$$\begin{aligned}&E\left[\Lambda\lambda p_1(c)\,k(S)\,y|\text{report}\right]+E\left[\Lambda\lambda p_1(0)\,k(R)\,y|\text{not report}\right]\\&\quad+E\left[\Gamma(1-\gamma)\,p_1(0)\,k(R)\,y\right]\end{aligned}$$

The marginal effect of raising sensitivity is

$$\begin{aligned}&-E\left[p_0q|\text{report}\right]\{p_1(0)\,k(R)\,y-p_1(c)\,k(S)\,y\}\\&-E\left[\Lambda|\text{report}\right]\left(\frac{\partial c}{\partial\alpha}+\frac{\partial S}{\partial\alpha}\right)-\left(E\left[\Lambda|\text{not report}\right]+E\left[\Gamma\right]\right)\frac{\partial R}{\partial\alpha}\\&-\{p_1(0)\,k(R)\,y-p_1(c)\,k(S)\,y\}\,E\left[p_0\alpha q_x\frac{\partial x}{\partial\alpha}|\text{report}\right]\end{aligned}$$

One the one hand, in the first term, sensitivity directly moves some outbreak states from the set of non-reported and high-loss cases to the set of reported and low-loss cases. Moreover, in the second term, sensitivity increases loss-reducing assistance and ex post sanctions in the reported cases. On the other hand, in the third term, sensitivity reduces loss-reducing preemptive sanctions in non-reported cases. Finally, to the extent that improvements in technological sensitivity reduces country investment in sensitivity, there may be, in the fourth term, some reversal of the direct effect of sensitivity in the first term. The marginal effect of raising specificity is just the the second line of the effect of sensitivity. This is enough, however, to generate ambiguous effects on loss of life. The culprit common to both technologies is the reduction in preemptive sanctions.

Not only have we demonstrated that technology may have ambiguous effects on surveillance, reporting and loss of life, but also it should be apparent that the return to specificity may not be negative. Indeed, it is possible that the return to specificity may exceed that to sensitivity. Consider the following example. Suppose one uses the immediate benefits of sensitivity and specificity as a rough proxy for the relative effects of innovation on reporting. Then specificity will be better for reporting than sensitivity if

$$r > \frac{1}{\alpha+\beta} + \frac{\alpha}{\alpha+\beta}\left[\frac{\Delta p_1\,(0,c)\,y}{S-R}\right] q$$

For countries who are remotely close to the margin for reporting, that is, for whom $\Delta p_1\,(0,c)\,y > S-R$, this condition suggests that specificity might be more productive than sensitivity when $\alpha+\beta > 1$, that is, the contribution of technology to the marginal productivity or surveillance is relatively high.

6 Rumors

In this section we examine the effect of introducing rumors and of correcting bad rumors on incentives for surveillance and reporting. The key difference between country reporting and rumors is that the latter are involuntary. This provides trading partners an additional source of information to motivate preemptive sanctions. (Positive rumors are redundant when a country reports.) Our primary finding is that either introducing rumors or improving the quality of rumors increases the incidence of preemptive sanctions because there will be more instances where a country does not report but rumors suggest an outbreak. Relative to improving the quality of testing, this will tend to promote reporting.

Rumors occur between stages 2 and 3 of the game, after a country detects an outbreak but before it decides whether to report.[13] For simplicity, we assume that the results of diagnostic testing and the content of rumors are independent. Let $\bar{q}$ and $\bar{r}$ be the sensitivity and specificity of rumors, respectively. Table 3 gives the joint probabilities of whether there is an outbreak, the result of diagnostic testing, and the content of rumors. Let $i = 1$ (0) indicate that test results are positive

[13] The model becomes simpler when the country reports at the same time as rumors are revealed. This means the country cannot take rumors into account in its reporting and thus surveillance decision. This is equivalent to ruling out cases 2 and 3 in the analysis that follows. From Proposition 5 it is clear the effect on investment in surveillance among reporting (case 1) countries is ambiguous. The effect on case 4 countries is zero. In our model, because it is assumed countries do not have their own medical resources, there is no point in conducting surveillance if one does not expect to report whether or not there are rumors.

Test	Rumor	Outbreak	No outbreak
$+$	$+$	$p_0 q \bar{q}$	$(1-p_0)(1-r)(1-\bar{r})$
$+$	-	$p_0 q (1-\bar{q})$	$(1-p_0)(1-r)\bar{r}$
-	$+$	$p_0 (1-q) \bar{q}$	$(1-p_0) r (1-\bar{r})$
-	-	$p_0 (1-q)(1-\bar{q})$	$(1-p_0) r \bar{r}$

Table 3: Joint probabilities of outbreaks, test results, and rumors.

(negative) for an outbreak. Let $j = 1$ (0) indicate rumors suggest that there is (is not) an outbreak in a country. Define Λ_{ij} as the probability of outcomes (i, j) from testing and rumors, respectively, and λ_{ij} (γ_{ij}) as the probability of an outbreak (no outbreak) conditional on outcomes (i, j) for all (i, j). As before, the probability of an outbreak and the results of testing are private information. Rumors, however, are common knowledge. Let $k = 1$ (0) if the country informs (does not inform) WHO and trading partners of a positive test result. Let c_{kj} and S_{kj} be medical assistance and ex post sanctions conditional on outcomes $(k = 1, j)$ for all j. Let R_{kj} be preemptive sanctions conditional on outcomes $(k = 0, j)$ for all j.

As in the last section, we ignore WHO subsidies for surveillance and assume that WHO medical assistance has no value in the absence of a positive test result. (A positive rumor does not identify exactly who is infected.) For further simplicity, we assume that technological sensitivity $q(x)$ and specificity $r(x)$ are each an increasing, concave function of a country's investment in surveillance. This implies that a country's payoffs conditional on test results, rumors and reporting decision are as set forth in Table 4. A country will report when both testing and rumors are positive if

$$\lambda_{11}^{SB} \Delta p_1 \left(0, c_{11}^{SB}\right) > S_{11}^{SB} - R_{01}^{SB}$$

It will report when testing is positive but rumors are negative if

$$\lambda_{01}^{SB} \Delta p_1 \left(0, c_{01}^{SB}\right) > S_{10} - R_{00}^{SB}$$

Test	Rumor	Report	Payoff
+	+	Y	$-x-z-\lambda_{11}p_1(c_{11})y-S_{11}$
+	+	N	$-x-z-\lambda_{11}p_1(0)y-R_{01}$
+	-	Y	$-x-z-\lambda_{10}p_1(c_{10})y-S_{10}$
+	-	N	$-x-z-\lambda_{10}p_1(0)y-R_{00}$
-	+	N	$-x-z-\lambda_{01}p_1(0)y-R_{01}$
-	-	N	$-x-z-\lambda_{00}p_1(0)y-R_{00}$

Table 4: Country payoffs conditional on test results, rumors and reporting decision.

Based on these criteria, we can write WHO's objective as

$$\max_c -E\left[\Lambda_{11}\left\{\lambda_{11}p_1(c_{11})k(S_{11})y-c_{11}\right\}|\text{report if } i=1, j=1\right]$$
$$-E\left[\Lambda_{10}\left\{\lambda_{10}p_1(c_{10})k(S_{10})y-c_{01}\right\}|\text{report if } i=1, j=0\right]$$

where we have omitted payoffs in states where the country does not produce a positive test result because WHO provides no assistance and therefore cannot affect payoffs in those states. Trading partners' payoff is

$$-E\left[\Lambda_{11}\left\{\lambda_{11}p_1(c_{11})k(S_{11})y-S_{11}\right\}|\text{report if } i=1, j=1\right]$$
$$-E\left[\Lambda_{10}\left\{\lambda_{10}p_1(c_{10})k(S_{10})y-S_{01}\right\}|\text{report if } i=1, j=0\right]$$
$$-E\left[\Lambda_{11}\left\{\lambda_{11}p_1(0)k(R_{01})y-R_{01}\right\}|\text{not report if } i=1, j=1\right]$$
$$-E\left[\Lambda_{10}\left\{\lambda_{10}p_1(0)k(R_{00})y-R_{00}\right\}|\text{not report if } i=1, j=0\right]$$
$$-E\left[\Lambda_{01}\left\{\lambda_{01}p_1(0)k(R_{01})y-R_{01}\right\}\right]-E\left[\Lambda_{00}\left\{\lambda_{00}p_1(0)k(R_{00})y-R_{00}\right\}\right]$$

Optimality conditions for WHO assistance and sanctions are straightforward. Because a country's reporting decision, in general, depends on a country's probability of an outbreak, optimality conditions for surveillance depends on the country's predictable reporting decisions. There are four cases to consider: (1) report if $(i=1, j=1)$ and $(i=1, j=0)$, (2) report if $(1,1)$ but not if $(1,0)$, (3) report if $(1,0)$ but not if $(1,1)$, (4) do not report. The optimality conditions for each case are:

$$
\begin{aligned}
\text{Case 1} &: \quad q_x^{SB} = \begin{bmatrix} p_0\bar{q}\left\{\Delta p_1\left(0, c_{11}^{SB}\right) y - S_{11}^{SB} + R_{01}^{SB}\right\} \\ +p_0\left(1-\bar{q}\right)\left\{\Delta p_1\left(0, c_{10}^{SB}\right) y - S_{01}^{SB} + R_{00}^{SB}\right\} \end{bmatrix}^{-1} \\
&\qquad\qquad\qquad r_x^{SB} \\
\text{Case 2} &: \quad q_x^{SB} = \left[p_0\bar{q}\left\{\Delta p_1\left(0, c_{11}^{SB}\right) y - S_{11}^{SB} + R_{01}^{SB}\right\}\right]^{-1} \\
\text{Case 3} &: \quad q_x^{SB} = \left[p_0\left(1-\bar{q}\right)\left\{\Delta p_1\left(0, c_{10}^{SB}\right) y - S_{01}^{SB} + R_{00}^{SB}\right\}\right]^{-1} \\
\text{Case 4} &: \quad x = 0
\end{aligned}
$$

Explanations of these conditions are similar to those for analogous conditions in previous sections.

We are interested in the consequences of improving the specificity and sensitivity of rumors on surveillance, reporting and expected loss of life. The following proposition summarize our findings.

Proposition 5 *An increase in either the sensitivity or specificity of rumors increases preemptive sanctions in the state where there is no report but rumors indicate there is an outbreak. It decreases preemptive sanctions in the state where there is no report and no rumors of an outbreak. Suppose assumption (A3) holds. Then an increase in either the sensitivity or specificity of rumors increases medical assistance and ex post sanctions when a country reports and rumors indicate there is an outbreak. It decreases medical assistance and ex post sanctions when a country reports but rumors do not indicate an outbreak. The effect on investment in the sensitivity and specificity of surveillance is ambiguous. Suppose further that (A5) the curvature of* p_1 *is sufficiently closer to the curvature of the exponential function such that*

$$\delta_{1i}\left|\tilde{K}_{1i}\right| > \left|\tilde{P}_{1i}\right|$$

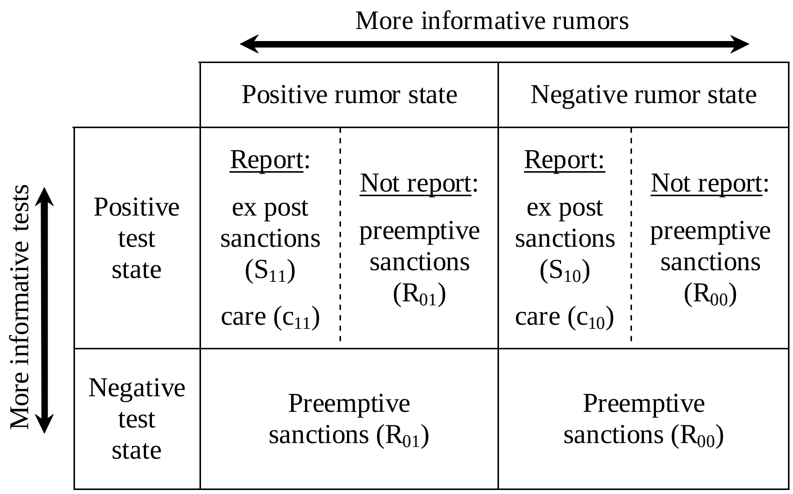

Figure 1: Contrasting effects of improved testing and improved rumors.

where

$$
\begin{aligned}
\delta_{1i} &= \frac{1}{k_{1i}}\left[\frac{E\left[\Lambda_{1i}|1,2\right]}{E\left[\Lambda_{1i}\lambda_{1i}|1,2\right]}\right] \lesseqgtr 1 \\
\tilde{K}_{1i} &= \left\{\frac{k''_{1i}}{(-k'_{1i})} - \frac{(-k'_{1i})}{k_{1i}}\right\}, \ \tilde{P}_{1i} = \left\{\frac{p''_{1i}}{(-p'_{1i})} - \frac{(-p'_{1i})}{p_{1i}}\right\} \\
k_{1i} &= k\left(S_{1i}\right), \ p_{1i} = p_1\left(c_{1i}\right)
\end{aligned}
$$

Then an increase in the sensitivity of rumors will increase investment in sensitivity by countries that report outbreaks when both their testing and rumors are positive for an outbreak and will decrease investment in sensitivity by countries that report outbreaks when their testing is positive for an outbreak but rumors are not.

Proof. See appendix. ■

Figure 1 helps explain this proposition. Increased sensitivity (specificity) of rumors moves true outbreak (no outbreak) cases from the negative (positive) rumor state to the positive (negative) rumor state. This sorting improves the informativeness of rumors. This in turn increases the return of ex post sanctions and preemptive sanctions to trading partners and of medical assistance to WHO when there is a positive rumor. It has the opposite effect when there is a negative rumor.

The reason is that a positive rumor is now more highly correlated with an actual outbreak, *whether or not a country reports.*

Contrast this to the effect of increasing the sensitivity or specificity, and thus informativeness, of testing. That increases the return to *ex post* sanctions and medical assistance when a country reports relative to preemptive sanctions when it does not. And this is true *whether or not there is a rumor.* The key observable difference is that, whereas improved rumors will increase preemptive sanctions when there is a positive rumor and decrease *ex post* sanctions and medical assistance when there is a negative rumor, improved testing will reduce preemptive sanctions when there is a positive rumor and increase *ex post* sanctions and medical assistance when there is a negative rumor.

The effect on surveillance is generally ambiguous. First consider investment in sensitivity of surveillance, which tends move true outbreak cases from the negative to the positive test result state. In the positive rumor state, among other things, greater medical assistance and greater preemptive sanctions encourage more investment but greater *ex post* sanctions discourage such investment. In the negative rumor state, one observes the opposite effects on medical assistance, preemptive sanctions and ex post sanctions, and therefore opposite effects on investment in sensitivity. But the net effect is still ambiguous.

Now consider investment in specificity of surveillance, which tends to move false outbreak cases from the positive test result to the negative test result state. Unlike sensitivity, specificity reduces application of *ex post* sanctions and increases the application of preemptive sanctions. Medical assistance is not relevant because we are dealing with actual no outbreak cases. Since we have flipped the role of *ex post* sanctions and preemptive sanctions, we observe a flip in the effect of improved rumors. For example, in the positive rumor state, higher preemptive sanctions discourage investment but greater *ex post* sanctions encourage such investment.

Because the effect of informativeness of rumors on surveillance is ambiguous, the effect on reporting is *a fortiori* ambiguous. There is, however, an important distinction between the effect of improved testing and the effect of improved rumors on reporting. Whereas improved testing reduces preemptive sanctions in the positive rumor state, improved rumors increase preemptive sanctions in the positive rumor state. Since greater preemptive sanctions encourage reporting, on a qualitative level there is less of a disincentive to report with improved rumors. We cannot confirm this quantitatively because improved testing may, for example, increase *ex post* sanctions less than improved rumors. But if we have no reason to think that testing and rumors have differential effects on *ex post* sanctions and medical assistance, then investments in improving rumors are less harmful to reporting than investments in improving testing.

7 Conclusion

As we discussed in the Prologue, the world was saved from China's failure to report its SARS outbreak by the good fortune of biology. The case fatality rate (percentage of infected patients that die) for SARS was around fifteen percent. The case fatality rate for the H5N1 strain of avian influenza, however, is much greater. Fifty-five countries have already discovered avian flu outbreaks in their domestic or wild bird populations (OIE, Feb. 19, 2007). And of the 285 confirmed cases of human infection since 2003, 170 or 60 percent have resulted in death (WHO, Mar. 29, 2007). Although the H5N1 strain has mastered animal-to-animal and animal-to-human transmission, it has fortunately not accomplished sustained human-to-human transmission. If that were to happen, WHO conservatively estimates that two to 7.4 million people might die (WHO Oct. 14, 2005). Others have estimated the loss as high as 62 million deaths (Murray et al. 2006).

WHO's strategy for preventing an epidemic relies on rapid vaccination and quarantine of the immediate neighborhood where human-to-human transmission is detected. That strategy relies, however, on early detection of an outbreak - typically within two weeks of the first instance of human-to-human transmission (Science, Jan. 20, 2006; Science, Feb. 24, 2006). Unfortunately, many countries, including Iran, Nigeria, Sudan, Tunisia and Turkey are reluctant to cooperate (VOA News

Mar. 3, 2006). Although China has reported outbreaks with greater speed than in the case of SARS, it has failed to report outbreaks in certain provinces (NYT Feb. 1, 2006; NYT, June 24, 2006). Moreover, China and Indonesia, which itself has suffered 63 human deaths from avian flu, have delayed sharing the blood samples that are vital to the development of a vaccine targeted precisely at the current strain of bird flu (WSJ Dec. 23, 2005; WSJ Dec. 27, 2005; WSJ Feb. 7, 2007).

In this paper we explored the private incentives of source countries to surveil and report information on disease outbreaks. The analysis not only sheds light on why countries have failed to cooperate fully on avian influenza, but also how better cooperation might be secured. More valuable medical assistance and perhaps transfers to offset the cost of ex post sanctions are useful; limits on sanctions, especially preemptive sanctions, are not. A useful policy may be for private markets to sell or the World Bank to provide source countries financial insurance against ex post sanctions. This insurance would compensate countries that suffer *ex post* sanctions but not stop the sanctions themselves. This would lessen the cost of *ex post* sanctions and thus reporting, but would not eliminate *ex post* sanctions and permit the spread of disease. It is important that insurance payments be triggered only by ex post sanctions and not preemptive sanctions, that is, a reported outbreak and not fears of an outbreak, else the relative cost of reporting would rise.

Importantly, the paper suggests that improved detection technology and a better system for informal reporting of disease outbreaks (rumor surveillance), two pillars of the WHO's strategy to track and control avian flu, are a mixed bag. On the one hand, technically more informative signals of disease outbreak are *a fortiori* more informative. On the other hand, more revealing signals can reduce countries' incentive to look for and report outbreaks.[14]

A broader underlying theme of this paper relates to the class of information acquisition and disclosure problems that involve multiple principals who have similar

[14] Although we have treated the reporting decision as binary, reporting has a qualitative element in the real world. For instance, Canada initially sought to play down the extent of the SARS outbreak in Toronto in the early days of the outbreak. Although Canada was technically reporting the outbreak, its initial reporting could have been more informative if there were not a strong disincentive to play down the problem.

interests but different levers and cannot cooperate. Our analysis suggests that problem of inadequate monitoring and disclosure with respect to, for example, STDs, student violence, and product defects is somewhat mitigated by the willingness of sexual partners, parents, and consumers to preemptively sanction (by refusing to deal) with possible carriers, schools and manufacturers, respectively. Moreover, in the absence of enforceable, mandatory monitoring and reporting, improving the technology of testing and audits or the quality of rumors and whistle-blowing may reduce monitoring and disclosure, leading to an increase in STDs, student violence, and product defects.

That said, there are a number of important extensions of the paper that ought to be explored before drawing serious policy-related conclusions. For example, the paper assumes that information on the probability of an outbreak is private information to the source country. It would be helpful to explore the case where it is not, or where there is repeat play that makes this information common knowledge. There would be greater potential for strategic interactions in such a case. Second, we assumed that source countries cannot affect the probability of an outbreak. If this is not the case, then there may a trade-off between *ex ante* infection control and *ex post* reporting. For instance, medical assistance to encourage reporting may reduce the expected cost of lax infection control. Third, we assumed a specific timeline of events. For instance, we posited that investment in surveillance preceded rumors. If, however, rumors precede investment decisions, then improving the quality of rumors will have more complicated effects on investment and reporting. An improvement in rumors may increase investment in sensitivity of testing following positive rumors and either increase the specificity of testing or decrease reporting following negative rumors. The reason is that positive rumors are not very helpful for identifying whom the source country ought to treat with WHO medical assistance. An increase in sensitivity of testing can make medical assistance that follows a positive rumor more productive. Likewise, a negative rumor will only avoid ex post sanctions if test results are also negative. This can be achieved either by increasing specificity of testing or by not reporting.

8 References

Arlen, Jennifer. 1994. “The Potentially Perverse Effects of Corporate Criminal Liability.” J. Legal Studies 23(2): 833-867.

Bergemann, Dirk, and Juuso Välimäki. 2005. "Information in Mechanism Design." Cowles Foundation Discussion Paper No. 1532.

Bernheim, B. Douglas and Michael D. Whinston. 1986. Common Agency. Econometrica 54(4): 923-942.

Blayney, Don P. Aug. 2005. “Disease-Related Trade Restrictions Shaped Animal Product Markets in 2004 and Stamp Imprints on 2005 Forecasts.” Electronic Outlook Report from Economic Research Service, United States Department of Agriculture LDP-M-133-01.

Brownstein, John S., Cecily J. Wolfe, and Kenneth D. Mandl. 2006. Empirical Evidence for the Effect of Airline Travel on Inter-Regional Influenza Spread in the United States." PLoS Medicine 3(10): e401.

Canadien Press. Sept. 9, 2003. “Health Canada working on SARS surveillance plan.” Accessed at http://www.ctv.ca/servlet/ArticleNews/ story/CTVNews/ 1063061919889_58471119/.

Cremer, Jacques, Fahad Khalil, and Jean-Charles Rochet. 1998. "Contracts and Productive Information Gathering." Games and Economic Behavior 25: 174-193.

Dixit, Avinash K. 1996. The Making of Economic Policy: A Transaction-Cost Politics Perspective. Cambridge, MA: MIT Press.

DrugResearcher.com. 2006. "CDC avian flu lab test dubbed quickest yet." Aug. 2. Available at http://www.drugresearcher.com/news-by-product/ news.asp?id=65684&idCat=&k=cdc-avian-flu.

Ewerhart, Christian and Patrick W. Schmitz. 2000. "’Yes Men,’ Integrity, and the Optimal Design of Incentive Contracts." Working paper.

Ferguson, N. M., D. A. T. Cummings, et al. 2005. “Strategies for containing an emerging influenza pandemic in Southeast Asia.” Nature 437(7056): 209-214.

Fox, Maggie. 2006. "Gene chip test identifies bird flu strains." Reuters, Nov. 13. Available at http://www.alertnet.org/thenews/newsdesk/N13211111.htm.

Gale, Douglas, and Martin Hellwig. 1985. "Incentive-compatible debt contracts: the one-period problem." Rev. of Econ. Studies 52: 647–663.

Gerberding, Julie L. 2005. "Statement by Julie L. Gerberding, M.D., M.P.H. Director Centers for Disease Control and Prevention U.S. Department of Health and Human Services on Influenza Preparedness before the Subcommittee on Labor/HHS/Education and Related Agencies Appropriations Subcommittee, United States House of Representatives, April 12, 2006." Available at http://www.hhs.gov/asl/testify/t050412b.html.

Grossman, Sanford J. 1981. "The Informational Role of Warranties and Private Disclosure about Product Quality." J. Law and Economics 24(3): 461-483.

Harris, Shane. 2006. "The bug bloggers." Bulletin of Atomic Scientists. 62(1): 38-43.

Heymann, David L., and Guenael Rodier. 2004. "Global Surveillance, National Surveillance, and SARS." Emerging Infectious Diseases 10(2): 173-175.

Jansen, Jos. 2004. "Information Acquisition and Stretegic Disclosure in Cournot Oligopoly." Social Science Research Center Berlin (WZB) working paper.

Kahn, Joseph. 2003. "Hong Kong stirs, Beijing frets Across the border, Chinese ask: Could it happen here?" Intl. Herald Trib. July 23: 1.

Kaplow, Louis, and Steven Shavell. 1994. "Optimal Law Enforcement with Self-Reporting of Behavior." J. Political Economy 102(3): 583-606.

Khalil, Fahad, David Martimort, and Bruno Parigi. 2007. "Monitoring a common agent: Implications for financial contracting." J. Economic Theory, forthcoming.

Krasa, Stefan, and Anne P. Villamil. 2000. "Optimal Contracts when Enforcement is a Decision Variable." Econometrica 68:119-134.

Lewis, Tracy R., and David E.M. Sappington. 1997. "Information Management in Incentive Problems." J. Political Economy 105(4): 796-821.

Longini, I. M., Jr., A. Nizam, et al. 2005. "Containing Pandemic Influenza at the Source." Science 309(5737): 1083-1087.

Matthews, Steven, and Andrew Postlewaite. 1985. "Quality Testing and Disclosure." RAND Journal of Economics 16(3): 328-340.

Milgrom, Paul R. 1981. "Good New and Bad News: Representation Theorems and Applications." Bell Journal of Economics 12(2): 380-391.

Mookerjee, Dilip and Ivan Png. 1989. "Optimal Auditing, Insurance, and Redistribution." Quarterly Journal of Economics 104: 399–415.

Murray, Christopher J.L., Lopez, Alan D., et al. 2006. "Estimation of potential global pandemic influenza mortality on the basis of vital registry data from the 1918-20 pandemic: a quantatative analysis." Lancet 368: 2211-2218.

New York Times. June 24, 2006. "Mystery Deepens on Possible Avian Flu Case in China in 2003." Accessed at: http://www.nytimes.com/2006/06/24/world/asia/24china.html?pagewanted=print.

New York Times. Feb. 1, 2006. "Bird Flu Case in Hong Kong Raises Questions About China."

New York Times. Oct. 8, 2006. "A Very Violent School, or Just Very Honest?" Accessed at: http://www.nytimes.com/2006/10/08/nyregion/08rome.html?_r=1&oref=slogin&pagewanted=print.

Office International des Épizooties (World Organisation for Animal Health). Feb. 19, 2007. "Update on Avian Influenza in Animals (Type H5)." Accessed at: http://www.oie.int/downld/AVIAN%20INFLUENZA/A_AI-Asia.htm.

Panisset, U. 2000. International Health Statecraft: Foreign Policy and Public Health in Peru's Cholera Epidemic. Lanham: University Press of America.

Polinsky, A. Mitchell, and Steven Shavell. 2006. "Mandatory versus Voluntary Disclosure of Product Risks." Stanford Law and Economics Olin Working Paper No. 327.

Prendergast, Canice. 1993. "A Theory of 'Yes Men.'" American Economic Review 83(4): 757-770.

Samaan, Gina, Mahomed Patel, Babatunde Olowokure, Maria C. Roces, Hitoshi Oshitani, and the World Health Organization Outbreak Response Team. 2005. "Rumor Surveillance and Avian Influenza H5N1." Emerging Infectious Diseases 11(3): 436-466.

Science. July 18, 2003. "China's Missed Chance." 301: 294-296.

Science. Jan. 20, 2006. "WHO Proposes Plan to Stop Pandemic in Its Tracks." 311: 315-16.

Science. Feb. 17, 2006. "Combating the Bird Flu Menace, Down on the Farm." 311: 944-946.

Science. Feb. 24, 2006. "New Study Casts Doubt on Plans for Pandemic Containment." 311: 1084.

Shavell, Steven. 1994. "Acquisition and disclosure of information prior to sale." RAND Journal of Economics 25(1): 20-36.

Tirole, Jean. 2001. "Corporate Governance." Econometrica 69(1): 1-36.

Townsend, M. B., E. D. Dawson, et al. 2006 . "Experimental Evaluation of the FluChip Diagnostic Microarray for Influenza Virus Surveillance." J. Clin. Microbiol. 44(8): 2863-2871.

Townsend, Robert. 1979. "Optimal contracts and competitive markets with costly state verification." Journal of Economic Theory 21: 265–293.

TTG Asia. Jan. 27 - Feb. 6, 2006. "Tourism takes a hit." Accessed at http://www.ttgasia.com/index.php?option=com_content &task=view &id=12071 &Itemid=48.

U.S. Department of Health and Human Servcies. 2006. "FDA Approves New Laboratory Test To Detect Human Infections With Avian Influenza A/H5 Viruses." Press Release, Feb. 3. Available at: http://www.hhs.gov/news/press/2006pres/20060203.html.

Voice of America News. Mar. 3, 2006. "UN Contractor: Countries Refuse to Co-operate in Bird Flu Investigation." Accessed at: http://www.voanews.com/english/2006-03-03-voa45.cfm."

Wall Street Journal. Nov. 11, 2003. "Beijing steps up bird-flu fight, enacts import ban." A10.

Wall Street Journal. Nov. 21, 2005. "Poultry From British Columbia Is Banned in U.S. Due to Bird Flu." A5.

Wall Street Journal. Dec. 23, 2005. "WHO Official Urges China To Share Bird-Flu Samples." Accessed at http://online.wsj.com/article_print/ SB113534754713 630527. html.

Wall Street Journal. Dec. 27, 2005. "Gaps seen in bird-flu alerts." A12.

Wall Street Journal. Feb. 7, 2007. "Indonesia Refuses to Share Bird-Flu Virus for Research." Accessed at: http://online.wsj.com/article/SB117078425088499758. html?mod=2_1177_1.

Williamson, Stephen D. 1986. "Costly monitoring, financial intermediation and equilibrium credit rationing." Journal of Monetary Economics 18, 159–179.

World Health Organization. May 20, 2003. "Severe acute respiratory syndrome (SARS): Status of the outbreak and lessons for the immediate future." http://www.who.int/csr/sars/resources/en/index.html.

World Health Organization. July 4, 2003. "Update 95 - SARS: Chronology of a serial killer." Accessed at http://www.who.int/csr/don/ 2003_07_04/en/.

World Health Organization. May 23, 2005. "World Health Assembly adopts new International Health Regulations." Accessed at http:// www.who.int/mediacentre/ news/releases/2005/pr_wha03/en/index.html.

World Health Organization. Oct. 14, 2005. "Ten things you need to know about pandemic influenza." Accessed at: http://www.who.int/csr/disease /influenza/ pandemic10things/en/index.html.

World Health Organization. 2005. "Responding to the avian influenza pandemic threat: Recommended strategic actions." Washington, DC.

World Health Organization. Mar. 3, 2006. "H5N1 avian influenza: timeline." Accessed at: http://www.who.int/entity/csr/disease/ avian_influenza/ Timeline_ 3_03.pdf.

World Health Organization. Mar. 29, 2007. "Cumulative Number of Confirmed Human Cases of Avian Influenza A/(H5N1) Reported to WHO." Accessed at: http://www.who.int/csr/disease/avian_influenza/country/cases_table_2007_ 02_19/ en/index.html.

Zamiska, Nicholas. Oct. 18, 2005. "Inside UN Agency, Flu Data Sparked a Tense Debate." Wall Street Journal.

A Proofs

Proof of Proposition 2. Suppose, in the second best formulation, one were to change the loss-of-surplus cost of sanctions to the country and trading partners from S to mS and the country's loss of life from an epidemic from y to nky. Performing comparative statics on the optimality conditions with respect to $m \geq 1$ reveals

$$\begin{aligned}
\frac{\partial c}{\partial m} &= \frac{p_1' k' y}{F} > 0, \ \frac{\partial S}{\partial m} = \frac{-p_1'' k y}{F} < 0 \\
\frac{\partial t}{\partial m} &= \frac{E\left[p_0 q_t\right]\left\{p_1'' k y - p_1' k' y\right\}}{E\left[p_0 q_{tt}\left\{p_1(0)k(0) - p_1(c)k(S)\right\} y - S\right] F} < 0
\end{aligned}$$

and $\partial x / \partial m$ is ambiguous, where the arguments of q, p_1 and k are ignored when they are obvious, all choice variables are at Nash values conditional on m, and $F = \left(p_1'' k y\right)\left(p_1 k'' y\right) - \left(p_1' k' y\right)^2$. These results imply

$$\begin{aligned}
\frac{\partial pky}{\partial m} &= \frac{p_1'' k y - m p_1' k' y}{F} > 0 \\
\frac{\partial W}{\partial m} &= \frac{S}{\Delta p_1 n k} + \frac{m\left(1 - Sk'/k\right)}{\Delta p_1 n k}\left(\frac{-p_1'' k y}{F}\right) + \frac{m S p_1' / \Delta p_1}{\Delta p_1 n k}\left(\frac{p_1' k' y}{F}\right) \lesseqgtr 0
\end{aligned}$$

where the reporting condition can be written $y > W = mS/\Delta p_1 n k$. Performing comparative statics with respect to $n \in [0,1]$ reveals no change in behavior except with respect to the reporting condition:

$$\frac{\partial W}{\partial n} = -\frac{W}{n} < 0$$

Proof of Proposition 3. Taking R as exogenous and performing comparative statics on the optimality conditions with respect to R reveals

$$\begin{aligned}
\frac{\partial c}{\partial R} &= \frac{\partial S}{\partial R} = 0 \\
\frac{\partial t}{\partial R} &= \frac{E\left[p_0 q_t\right]}{E\left[p_0 q_{tt}\right]} \frac{p_1\left(0\right) k'\left(R\right) y}{B} < 0 \\
\frac{\partial x}{\partial R} &= \frac{\begin{array}{c}\left\{E\left[p_0 q_t\right] p_1\left(0\right) k'\left(R\right) y\right\}\left\{p_0 q_{xt} A\right\} \\ -\left\{p_0 q_x\right\}\left\{E\left[p_0 q_{tt}\right] B\right\}\end{array}}{\left\{p_0 q_{xt} A\right\}\left\{E\left[p_0 q_{tt}\right] B\right\}}
\end{aligned}$$

where the arguments of q are ignored when they are obvious, all choice variables (except R) are at Nash values, and

$$\begin{aligned}
A &= \Delta p_1\left(o, c\right) y - S + R \\
B &= p_1\left(0\right) k\left(R\right) y - p_1\left(c\right) k\left(S\right) y - c
\end{aligned}$$

If $q_{xt} \leq 0$, the last term is positive. Further, if $q = q\left(x + t\right)$ and x and t are perfect substitutes, then

$$\frac{\partial x^{SB}}{\partial R} = \frac{p_0 q_x^2}{-q_{xx}} > 0$$

Taking $R = R^{SB}$ when it is endogenous does not change the results.

Proof of Proposition 4. Define $h = 1$ (0) if a country reports (does not report). Comparative statics on the optimality conditions for (R, c, S, x, z) with respect to α and β yield

$$\begin{aligned}
\frac{\partial R}{\partial \alpha} &= -\frac{A_R}{F_R},\ \frac{\partial c}{\partial r} = \frac{A_S K}{LF},\ \frac{\partial S}{\partial r} = \frac{A_S P}{LF} \\
\frac{\partial x}{\partial \alpha} &= \frac{A_R\left\langle -p_0 \alpha q_x\right\rangle}{F_x F_R} + \frac{1}{F_x LF} D_1 \\
\frac{\partial z}{\partial \alpha} &= \frac{1}{F_z F_R}\left\langle \left(1 - p_0\right) r_z\right\rangle A_R \\
\frac{\partial R}{\partial \beta} &= \frac{B}{-F_R} < 0,\ \frac{\partial c}{\partial \beta} = \frac{BK}{LF},\ \frac{\partial S}{\partial r} = \frac{BP}{LF} \\
\frac{\partial x}{\partial \beta} &= \frac{B\left\langle -p_0 \alpha q_x\right\rangle}{F_x F_R} + \frac{1}{F_x LF} D_2 \\
\frac{\partial z}{\partial \beta} &= \frac{\left\langle \left(1 - p_0\right) r_z\right\rangle B}{F_R F_z} - \frac{1}{L^2 F F_z} D_2
\end{aligned}$$

where

$$
\begin{aligned}
F &= \begin{vmatrix} -p_1''(c)\,k(S)\,y & -p_1'(c)\,k'(S)\,y \\ -p_1'(c)\,k'(S)\,y & -p_1(c)\,k''(S)\,y \end{vmatrix},\ L = E[\Lambda\lambda|h=1] \\
F_x &= p_0\alpha q_{xx}(x)\left[\Delta p_1(0,c)\,y - S + R\right] < 0 \\
F_z &= -(1-p_0)\,\beta r_{zz}(z)\,[S-R] > 0 \\
F_R &= \{E[\Lambda\lambda|h=0] + E[\Gamma(1-\gamma)]\}\,p_1(0)\,k''(R)\,y > 0 \\
A_S &= -E[p_0 q|h=1]\left\{1 + p_1(c)\,k'(S)\,y\right\} > 0 \\
A_R &= -E[p_0 q|h=1]\left\{1 + p_1(0)\,k'(R)\,y\right\} > 0 \\
B &= E[(1-p_0)\,r|h=1] > 0 \\
D_1 &= \langle -p_0 q_x[\Delta p_1 y - S + R]\rangle L^2 F + A_S L\langle p_0\alpha q_x\rangle\left\langle P + p_1' y K\right\rangle \\
D_2 &= B_S L\langle p_0\alpha q_x\rangle\left\langle P + p_1' y K\right\rangle \\
P &= \left[\left(\frac{p_1''}{-p_1'}\right) - \left(\frac{-p_1'}{p_1}\right)\right],\ K = \left[\left(\frac{k''}{-k'}\right) - \left(\frac{-k'}{k}\right)\right]
\end{aligned}
$$

The optimality condition for R implies $1 + p_1(0)\,k'(R)\,y < 0$, so $A_R > 0$ and $\partial R/\partial\alpha < 0$ and $\partial z/\partial\alpha > 0$. It is helpful to observe that $B = E[(1-p_0)\,r|h=1] = E[(1-p_0)\,r|h=0] - E[(1-p_0)\,r] > 0$. Therefore, $\partial R/\partial\beta < 0$ and $\partial z/\partial\beta > 0$. Likewise, the optimality condition for c and S imply $1 + p_1'(c)\,k(S)\,y = 1 + p_1(c)\,k'(S)\,y < 0$, so $A_S > 0$. Further, if (A3) holds, then $K, P, F > 0$ $[< 0]$. This implies that $\partial c/\partial\alpha$, $\partial S/\partial\alpha$, $\partial c/\partial\beta$, $\partial S/\partial\beta > 0$. If (A4) holds, then D_1, $D_2 < 0$ and $\partial x/\partial\alpha$, $\partial x/\partial\beta < 0$. Then

Proof of Proposition 5. Comparative statics on the optimality conditions for the model with rumors reveals

$$\begin{aligned}
\frac{\partial c_{11}}{\partial \bar{q}} &= \frac{A_{11}K_{11}}{L_{11}F_{11}},\ \frac{\partial S_{11}}{\partial \bar{q}} = \frac{A_{11}P_{11}}{L_{11}F_{11}} \\
\frac{\partial c_{11}}{\partial \bar{r}} &= \frac{B_{11}K_{11}}{L_{11}F_{11}},\ \frac{\partial S_{11}}{\partial \bar{r}} = \frac{B_{11}P_{11}}{L_{11}F_{11}} \\
\frac{\partial R_{01}}{\partial \bar{q}} &= \frac{-A_{01}}{-F_{01}} > 0,\ \frac{\partial R_{01}}{\partial \bar{r}} = \frac{-B_{01}}{-F_{01}} > 0 \\
\frac{\partial c_{10}}{\partial \bar{q}} &= \frac{-A_{10}K_{10}}{L_{10}F_{10}},\ \frac{\partial S_{10}}{\partial \bar{q}} = \frac{-A_{10}P_{10}}{L_{10}F_{10}} \\
\frac{\partial c_{10}}{\partial \bar{r}} &= \frac{-B_{10}K_{10}}{L_{10}F_{10}},\ \frac{\partial S_{10}}{\partial \bar{r}} = \frac{-B_{10}P_{10}}{L_{10}F_{10}} \\
\frac{\partial R_{00}}{\partial \bar{q}} &= \frac{A_{00}}{-F_{00}} < 0,\ \frac{\partial R_{00}}{\partial \bar{r}} = \frac{B_{00}}{-F_{00}} < 0
\end{aligned}$$

$$\begin{aligned}
\frac{\partial x_1}{\partial \bar{q}} = &\left[\tilde{F}_{11}\tilde{F}_{10}F_{01}F_{00}F_{x1}\right]^{-1} \times \\
&\{A_{11}L_{11}\tilde{F}_{10}F_{01}F_{00}\left\langle p_0\bar{q}q_x\right\rangle [\overbrace{\left(-p_{11}'y\right)K_{11}}^{\text{effect of } c_{11}>0} - \overbrace{P_{11}}^{\text{effect of } S_{11}<0}] \\
&+A_{10}L_{10}\tilde{F}_{11}F_{01}F_{00}\left\langle p_0\left(1-\bar{q}\right)q_x\right\rangle [\overbrace{P_{10}}^{\text{effect of } S_{10}>0} - \overbrace{\left(-p_{10}'y\right)K_{10}}^{\text{effect of } c_{10}<0}] \\
&+\overbrace{A_{01}\left\langle p_0\bar{q}q_x\right\rangle \tilde{F}_{11}\tilde{F}_{10}F_{00}}^{\text{effect of } R_{01}>0} - \overbrace{A_{00}\left\langle p_0\left(1-\bar{q}\right)q_x\right\rangle \tilde{F}_{11}\tilde{F}_{10}F_{01}}^{\text{effect of } R_{00}<0} \\
&+\overbrace{\left\langle A_{x1}\right\rangle \tilde{F}_{11}\tilde{F}_{10}F_{01}F_{00}}^{\text{direct effect} \gtreqless 0}\}
\end{aligned}$$

$$\begin{aligned}
\frac{\partial x_2}{\partial \bar{q}} &= \left[\tilde{F}_{11}F_{01}F_{x2}\right]^{-1} \times \\
&\quad \{A_{11}L_{11}F_{01}\left\langle p_0\bar{q}q_x\right\rangle [\overbrace{\left(-p_{11}'y\right)K_{11}}^{\text{effect of } c_{11}>0} - \overbrace{P_{11}}^{\text{effect of } S_{11}<0}] \\
&\quad +\overbrace{A_{01}\left\langle p_0\bar{q}q_x\right\rangle \tilde{F}_{11}}^{\text{effect of } R_{01}>0} + \overbrace{A_{x2}\tilde{F}_{11}F_{01}}^{\text{direct effect}>0}\} \\
\frac{\partial x_3}{\partial \bar{q}} &= \left[\tilde{F}_{10}F_{00}F_{x3}\right]^{-1} \times \\
&\quad \{A_{10}F_{00}L_{10}\left\langle p_0\left(1-\bar{q}\right)q_x\right\rangle [\overbrace{P_{10}}^{\text{effect of } S_{10}>0} - \overbrace{\left(-p_{10}'y\right)K_{10}}^{\text{effect of } c_{10}<0}] \\
&\quad \overbrace{-A_{00}\left\langle p_0\left(1-\bar{q}\right)q_x\right\rangle \tilde{F}_{10}}^{\text{effect of } R_{00}<0} - \overbrace{\tilde{F}_{10}F_{00}A_{x3}}^{\text{direct effect}<0}\}
\end{aligned}$$

$$\frac{\partial z_1}{\partial \bar{q}} = \left[\tilde{F}_{11}\tilde{F}_{10}F_{01}F_{00}F_{z1}\right]^{-1} \times$$

$$\{A_{11}\left\langle (1-p_0)(1-\bar{r})\, r_z\right\rangle \tilde{F}_{10}F_{01}F_{00}L_{11}P_{11} \quad \text{(effect of } S_{11}>0)$$

$$-A_{10}\left\langle (1-p_0)\,\bar{r}r_z\right\rangle \tilde{F}_{11}F_{01}F_{00}L_{10}P_{10} \quad \text{(effect of } S_{10}<0)$$

$$-A_{01}\left\langle (1-p_0)(1-\bar{r})\, r_z\right\rangle \tilde{F}_{11}\tilde{F}_{10}F_{00} \quad \text{(effect of } R_{01}<0)$$

$$A_{00}\left\langle (1-p_0)\,\bar{r}r_z\right\rangle \tilde{F}_{11}\tilde{F}_{10}F_{01}\} \quad \text{(effect of } R_{00}>0)$$

$$\begin{aligned}\frac{\partial z_2}{\partial \bar{q}} &= \left[\tilde{F}_{11}F_{01}F_{z2}\right]^{-1} \times \\ &\quad \{A_{11}\left\langle (1-p_0)(1-\bar{r})\, r_z\right\rangle F_{01}L_{11}P_{11} \quad \text{(effect of } S_{11}>0) \\ &\quad -A_{01}\left\langle (1-p_0)(1-\bar{r})\, r_z\right\rangle \tilde{F}_{11}\} \quad \text{(effect of } R_{01}<0) \\ \frac{\partial z_3}{\partial \bar{q}} &= \left[\tilde{F}_{10}F_{00}F_{z3}\right]^{-1} \times \\ &\quad \{-A_{10}\left\langle (1-p_0)\,\bar{r}r_z\right\rangle F_{00}L_{10}P_{11} \quad \text{(effect of } S_{10}<0) \\ &\quad A_{00}\left\langle (1-p_0)\,\bar{r}r_z\right\rangle \tilde{F}_{10}\} \quad \text{(effect of } R_{00}>0)\end{aligned}$$

$$\frac{\partial x_1}{\partial \bar{r}} = \left[\tilde{F}_{11}\tilde{F}_{10}F_{01}F_{00}F_{x1}\right]^{-1} \times$$

$$\{B_{11}L_{11}\tilde{F}_{10}F_{01}F_{00}\left\langle p_0\bar{q}q_x\right\rangle P_{11} \quad \text{(effect of } S_{11}>0)$$

$$-B_{10}L_{10}\tilde{F}_{11}F_{01}F_{00}\left\langle p_0(1-\bar{q})\, q_x\right\rangle P_{10} \quad \text{(effect of } S_{10}<0)$$

$$-\overbrace{B_{01}\left\langle p_0\bar{q}q_x\right\rangle \tilde{F}_{11}\tilde{F}_{10}F_{00}}^{\text{effect of } R_{01}<0} + \overbrace{B_{00}\left\langle p_0(1-\bar{q})\, q_x\right\rangle \tilde{F}_{11}\tilde{F}_{10}F_{01}}^{\text{effect of } R_{00}>0}$$

$$\begin{aligned}\frac{\partial x_2}{\partial \bar{r}} &= \left[\tilde{F}_{11}F_{01}F_{x2}\right]^{-1} \times \\ &\quad \{B_{11}L_{11}F_{01}\left\langle p_0\bar{q}q_x\right\rangle \overbrace{\left\langle P_{11}\right\rangle}^{\text{effect of } S_{11}>0} - \overbrace{B_{01}\left\langle p_0\bar{q}q_x\right\rangle \tilde{F}_{11}}^{\text{effect of } R_{01}<0}\} \\ \frac{\partial x_3}{\partial \bar{r}} &= \left[\tilde{F}_{10}F_{00}F_{x3}\right]^{-1} \times \\ &\quad \{B_{10}L_{10}F_{00}\left\langle p_0(1-\bar{q})\, q_x\right\rangle \overbrace{\left\langle -P_{10}\right\rangle}^{\text{effect of } S_{10}<0} + \overbrace{B_{00}\left\langle p_0(1-\bar{q})\, q_x\right\rangle \tilde{F}_{10}}^{\text{effect of R}_{00}>0}\}\end{aligned}$$

$$
\begin{aligned}
\frac{\partial z_1}{\partial \bar{r}} = & \left[\tilde{F}_{11}\tilde{F}_{10}F_{01}F_{00}F_{z1}\right]^{-1} \times \\
& \{B_{11}\left\langle (1-p_0)(1-\bar{r})\, r_z \right\rangle \tilde{F}_{10}F_{01}F_{00}L_{11}P_{11} && \text{(effect of } S_{11} > 0) \\
& -B_{10}\left\langle (1-p_0)\,\bar{r}r_z \right\rangle \tilde{F}_{11}F_{01}F_{00}L_{10}P_{10} && \text{(effect of } S_{10} < 0) \\
& -B_{01}\left\langle (1-p_0)(1-\bar{r})\, r_z \right\rangle \tilde{F}_{11}\tilde{F}_{10}F_{00} && \text{(effect of } R_{01} < 0) \\
& B_{00}\left\langle (1-p_0)\,\bar{r}r_z \right\rangle \tilde{F}_{11}\tilde{F}_{10}F_{01} && \text{(effect of } R_{00} > 0) \\
& B_{z1}\tilde{F}_{11}\tilde{F}_{10}F_{01}F_{00}\} && \text{(direct effect } \lesseqgtr 0)
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial z_2}{\partial \bar{q}} &= \left[\tilde{F}_{11}F_{01}F_{z2}\right]^{-1} \times \\
& \quad \{B_{11}\left\langle (1-p_0)(1-\bar{r})\, r_z \right\rangle F_{01}L_{11}P_{11} && \text{(effect of } S_{11} > 0) \\
& \quad -B_{01}\left\langle (1-p_0)(1-\bar{r})\, r_z \right\rangle \tilde{F}_{11}\} && \text{(effect of } R_{01} < 0) \\
& \quad -B_{z2}\tilde{F}_{11}F_{01}\} && \text{(direct effect } < 0) \\
\frac{\partial z_3}{\partial \bar{q}} &= \left[\tilde{F}_{10}F_{00}F_{z3}\right]^{-1} \times \\
& \quad \{-B_{10}\left\langle (1-p_0)\,\bar{r}r_z \right\rangle F_{00}L_{10}P_{11} && \text{(effect of } S_{10} < 0) \\
& \quad B_{00}\left\langle (1-p_0)\,\bar{r}r_z \right\rangle \tilde{F}_{10}\} && \text{(effect of } R_{00} > 0) \\
& \quad + B_{z3}\tilde{F}_{11}F_{01}\} && \text{(direct effect } > 0)
\end{aligned}
$$

where

$$
\begin{aligned}
A_{11} &= -E\left[p_0q|1,2\right]\left\{1+p_{11}k'_{11}y\right\} = -E\left[p_0q|1,2\right]\left\{1+p'_{11}k_{11}y\right\} > 0 \\
A_{10} &= -E\left[p_0q|1,3\right]\left\{1+p_{10}k'_{10}y\right\} = -E\left[p_0q|1,3\right]\left\{1+p'_{10}k_{10}y\right\} > 0 \\
A_{01} &= -\left\{E\left[p_0\right]-E\left[p_0q|1,2\right]\right\}\left\{1+p_1(0)\,k'(R_{01})\,y\right\} > 0 \\
A_{00} &= -\left\{E\left[p_0\right]-E\left[p_0q|1,3\right]\right\}\left\{1+p_1(0)\,k'(R_{00})\,y\right\} > 0 \\
A_{x1} &= -p_0q_x\left[G_{11}-G_{10}\right], \quad A_{x2} = p_0q_xG_{11} > 0, \quad A_{x3} = p_0q_xG_{10} > 0
\end{aligned}
$$

$$
\begin{aligned}
B_{11} &= E\left[(1-p_0)(1-r)|1,2\right] > 0, \quad B_{10} = E\left[(1-p_0)(1-r)|1,3\right] > 0 \\
B_{01} &= E\left[(1-p_0)|3,4\right] + E\left[(1-p_0)r|1,2\right] > 0 \\
B_{01} &= E\left[(1-p_0)|2,4\right] + E\left[(1-p_0)r|1,3\right] > 0 \\
B_{z1} &= -(1-p_0)r_z\left[(S_{10}-R_{00})-(S_{11}-R_{10})\right] \\
B_{z2} &= (1-p_0)r_z(S_{11}-R_{01}) > 0, \quad B_{z3} = (1-p_0)r_z(S_{10}-R_{00}) > 0
\end{aligned}
$$

$$
\begin{aligned}
F_{11} &= \left(p''_{11}k_{11}y\right)\left(p_{11}k''_{11}y\right) - \left(p_{11}k_{11}y\right)^2 > 0 \\
F_{10} &= \left(p_{10}k_{10}y\right)\left(p_{10}k_{10}y\right) - \left(p_{10}k_{10}y\right)^2 > 0 \\
\tilde{F}_{11} &= (L_{11})^2 F_{11}, \quad \tilde{F}_{10} = (L_{10})^2 F_{10} \\
F_{01} &= \left\{E\left[\Lambda_{11}\lambda_{11}|3,4\right] + E\left(\Lambda_{01}\lambda_{01}\right)\right\} p_1(0)\, k''(R_{01})\, y > 0 \\
F_{00} &= \left\{E\left[\Lambda_{10}\lambda_{10}|2,4\right] + E\left(\Lambda_{00}\lambda_{00}\right)\right\} p_1(0)\, k''(R_{00})\, y > 0 \\
F_{x1} &= -p_0 q_{xx}\left[\bar{q}G_{11} + (1-\bar{q})G_{10}\right] > 0 \\
F_{x2} &= -p_0 q_{xx}\bar{q}G_{11} > 0, \quad F_{x3} = -p_0 q_{xx}(1-\bar{q})G_{10} > 0 \\
F_{z1} &= -(1-p_0)r_{zz}\left[(1-\bar{r})(S_{11}-R_{01}) + \bar{r}(S_{10}-R_{00})\right] > 0 \\
F_{z2} &= -(1-p_0)r_{zz}(1-\bar{r})(S_{11}-R_{01}) > 0 \\
F_{z3} &= -(1-p_0)r_{zz}\bar{r}(S_{10}-R_{00}) > 0
\end{aligned}
$$

$$
G_{11} = \lambda_{11}\Delta p(0,c_{11})\,y - S_{11} + R_{01}, \quad G_{10} = \lambda_{10}\Delta p(0,c_{10})\,y - S_{10} + R_{00}
$$

$$
\begin{aligned}
L_{11} &= E\left[\Lambda_{11}\lambda_{11}|1,2\right] > 0, \quad L_{10} = E\left[\Lambda_{10}\lambda_{10}|1,3\right] > 0 \\
K_{11} &= p_{11}k''_{11}y - p'_{11}k'_{11}y, \quad P_{11} = p''_{11}k_{11}y - p'_{11}k'_{11}y \\
K_{10} &= p_{10}k''_{10}y - p'_{10}k'_{10}y, \quad P_{10} = p''_{10}k_{10}y - p'_{10}k'_{10}y
\end{aligned}
$$

where $E[\cdot|1,2]$,for example, indicates expectation taken over $f(p_0)$ conditional on countries in cases 1 and 2.

If (p_1, k) are log-convex (log-concave), then $F_{11}, F_{10}, P_{11}, K_{11}, P_{10}, K_{10} > 0$ (< 0).

This in turn implies,

$$\begin{aligned}
\frac{\partial c_{11}}{\partial \bar{q}}, \frac{\partial S_{11}}{\partial \bar{q}}, \frac{\partial c_{11}}{\partial \bar{r}}, \frac{\partial S_{11}}{\partial \bar{r}} &> 0 \\
\frac{\partial c_{10}}{\partial \bar{q}}, \frac{\partial S_{10}}{\partial \bar{q}}, \frac{\partial c_{10}}{\partial \bar{r}}, \frac{\partial S_{10}}{\partial \bar{r}} &< 0
\end{aligned}$$

Employing the optimality conditions for medical assistance and ex post sanctions, note that K_{1i} and P_{1i} can be written

$$\begin{aligned}
\left[\frac{E\left[\Lambda_{1i}|1,3-i\right]}{E\left[\Lambda_{1i}\lambda_{1i}|1,3-i\right]}\right]\left\{\frac{k''_{1i}}{(-k'_{1i})} - \frac{(-k'_{1i})}{k_{1i}}\right\} &\equiv \left[\frac{E\left[\Lambda_{1i}|1,3-i\right]}{E\left[\Lambda_{1i}\lambda_{1i}|1,3-i\right]}\right]\tilde{K}_{1i} \\
\left[\frac{E\left[\Lambda_{1i}|1,3-i\right]}{E\left[\Lambda_{1i}\lambda_{1i}|1,3-i\right]}\right]\left\{\frac{p''_{1i}}{(-p'_{1i})} - \frac{(-p'_{1i})}{p_{1i}}\right\} &\equiv \left[\frac{E\left[\Lambda_{1i}|1,3-i\right]}{E\left[\Lambda_{1i}\lambda_{1i}|1,3-i\right]}\right]\tilde{P}_{1i}
\end{aligned}$$

for $i = 0, 1$. If (A4) holds, that is,

$$\frac{1}{k_{11}}\left[\frac{E\left[\Lambda_{11}|1,2\right]}{E\left[\Lambda_{11}\lambda_{11}|1,2\right]}\right]\left|\tilde{K}_{11}\right| > \left|\tilde{P}_{11}\right|$$

and the curvature of p_1 is sufficiently closer to that of the exponential function than is the curvature of k, then $(-p'_{1i}y)\,K_{1i} - P_{1i} > 0$ and

$$\frac{\partial x_2}{\partial \bar{q}} > 0, \ \frac{\partial x_3}{\partial \bar{q}} < 0$$

B Equilibrium with unraveling

To demonstrate how preemptive sanctions can generate an equilibrium will unraveling as in Grossman (1981) and Milgrom (1981), consider the model from Section 4 with three modifications. First, for simplicity, we ignore WHO subsidies for surveillance. This variable complicates the model but does not add to the economic insights. Second, index countries by subscript i. Thus country i's probability of an outbreak is p_{0i}. WHO and a country's trading partners do not know this probability, but they do know the distribution of p_{0i} among all countries. Third, a country can credibly reveal its exact probability of an outbreak by submitting to an audit by WHO. This decision occurs at the start of the game. (Whether a country submits to an audit is common knowledge.) An audit is not without cost, however. If a country submits to an audit, it cannot conceal a positive test result from its surveillance. In other words, we consider a multiple country model with asymmetric information that can be credibly revealed via a "costly" audit.

Each country faces two choices, whether or not to submit to a WHO audit and how much to invest in surveillance. (In this model, surveillance is subject to false negatives, but no false positives.) The country's payoffs if it does and does not submit to an audit are

$$\Pi\left(\text{audit}\right) = -\Lambda_i \left(\lambda_i p_1\left(c_i\right) y + S_i\right) - \Gamma_i \left(\left(1-\gamma_i\right) p_1\left(0\right) y + R_{Ai}\right) \tag{17}$$

$$\Pi\left(\text{no audit}\right) = -p_1\left(0\right) y - R_N \tag{18}$$

respectively, where R_{Ai} and R_N are preemptive sanctions conditional on whether the country submits to an audit,

$$\begin{aligned}
\Lambda_i &= \Pr\left(\text{positive test}\right) = p_{0i} q\left(x_i\right) \\
\Gamma_i &= \Pr\left(\text{negative test}\right) = p_{0i}\left(1 - q\left(x_i\right)\right) + \left(1 - p_{0i}\right) \\
\lambda_i &= \Pr\left(\text{outbreak} \mid \text{positive test}\right) = 1 \\
\gamma_i &= \Pr\left(\text{outbreak} \mid \text{negative test}\right) = \left(1 - p_{0i}\right)/\Gamma_i
\end{aligned}$$

Note that, when a country submits to an audit, trading partners set sanctions (S_i, R_{Ai}) and WHO provides medical care c_i tailored to that country's specific probability of an outbreak because the audit credibly reveals this probability.

All countries that find it privately optimal to report will also submit to an audit because there is no additional cost to doing so. Therefore, we focus our analysis on the set of countries that do not find it privately optimal to report. For this set of countries, sanctions are more costly than the medical assistance from reporting: $S_i - R_{Ai} > \Delta p_1\left(0, c_i\right) y$. A country that would not otherwise report will submit to an audit, however, if (17) is greater than (18) or

$$p_{0i} < \frac{1}{q(x_i, t_i)} \left(\frac{R_N - R_{Ai}}{S_i - R_{Ai} - \Delta p_1(0, c_i) y} \right) = W(x_i, S, R_N, R_{Ai}, c_i) \tag{19}$$

A country that does not find it privately optimal to report will invest nothing in surveillance:

$$q_x = \frac{1}{p_{0i} (\Delta p_1(0, c_i) y - S_i + R_{Ai})} < 0$$

Trading partners must choose $2n+1$ variables. If country i submits to an audit, they must choose (S_i, R_{Ai}). For any country that does not submit to an audit, the trading partners must choose R_N. The objective functions for choosing these variables are

$$-\Lambda_i (p_1(c_i) [k(S_i) - 1] y - S_i) - \Gamma_i ((1 - \gamma_i) p_i(0) [k(R_{Ai}) - 1] y - R_{Ai}) \text{ for all } i$$

$$-E(p_0 | \text{no audit}) p_1(0) [k(R_N - 1) y] - R_N$$

The optimality conditions for these variables are:

$$S_i \; : \; -p_1(c_i) k'(S_i) y - 1 = 0 \text{ for all } i \tag{20}$$

$$R_{Ai} \; : \; -\Gamma_i (1 - \gamma_i) p_1(0) k'(R_{Ai}) y - 1 = 0 \text{ for all } i \tag{21}$$

$$R_N \; : \; -E(p_0 | \text{no audit}) p_1(0) k'(R_N) y - 1 = 0 \tag{22}$$

WHO must choose n variables. If country i submits to an audit, it must report positive test results. Therefore, WHO must decide how much medical care to provide when this happens. WHO's objective function and optimality conditions for care given p_{0i} are

$$-\Lambda_i (p_1(c_i) k(S_i) y - c_i) - \Gamma_i ((1 - \gamma_i) p_1(0) k(R_{Ai}) y) - t$$

$$-p_1(c_i') k(S_i) y - 1 = 0$$

respectively.

There are two steps to demonstrating the existence of an equilibrium with unraveling. First, we must show that the numerator of (19) is positive for some country and, therefore, that country seeks an audit. Take any country with a $p_{0i} < E(p_0|\text{no report})$. For that country, $\Gamma_i(1-\gamma_i) = p_{0i}(1-q(0,t_i)) < E(p_0|\text{no audit})$. From (21) and (22) then, $R_{Ai} < R_N$. The second step is to show that the optimality conditions for $(x_i, S, R_N, R_{Ai}, c_i)$ imply that the cutoff W_i exceeds one and therefore all countries submit to an audit. Performing comparative statics on the optimality conditions with respect to $E(p_0|\text{no audit})$ reveals that $\partial R_N/\partial E(p_{0i}|\text{no audit}) = -k'(R_N)/k''(R_n)E(p_{0i}|\text{no audit}) > 0$ and that none of the other choice variables are sensitive to changes in $E(p_0|\text{no audit})$. Therefore, $\partial W_i/\partial E(p_0|\text{no audit}) > 0$. Suppose $E(p_0|\text{no audit})$ starts out at $E(p_0|\text{no report})$. At this value for $E(p_{0i}|\text{no audit})$, all countries that would not report but that satisfy (19) submit to an audit. This causes trading partners to revise upwards their estimate of $E(p_0|\text{no audit}) > E(p_0|\text{no report})$. This upward revision in turn raises R_N and thus the cutoff W_i. The additional countries that satisfy (19) submit to an audit. Assuming there is no gap in the distribution of countries' p_{0i} above $E(p_{0i}|\text{no report})$ that is greater than the incremental revision of $E(p_{0i}|\text{no audit})$, this process continues until W_i rises above one. Because all players can engage in this logic before making their first move, all countries that would not report anticipate that the W_i which satisfies both (19) and the optimality conditions for $(x_i, S_i, R_N, R_{Ai}, c_i)$ is greater than one.