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Managing the endogenous risk of disease outbreaks with non-constant background risk

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ABSTRACT

There is a growing concern that risks of disease outbreak and pandemics are increasing over time. We consider optimal investments in prevention before an outbreak using an endogenous risk approach within an optimal control setting. Using the threat of pandemic influenza as an illustrative example, we demonstrate that prevention expenditures are relatively small in comparison to the potential losses facing the USA, and these expenditures need to be flexible and responsive to changes in background risk. Failure to adjust these expenditures to changes in background risk poses a significant threat to social welfare into the future.

1. Introduction

The natural science community has warned policymakers of the increased health risks from disease outbreaks for both emerging and extant pathogens (e.g., Cohen, 2000, Morens et al., 2004; Weiss and McMichael, 2004; Jones et al., 2008; Morse et al. 2012). Many factors drive the threat of emerging infectious disease (EID) including increased urbanization in developing countries that brings humans into new contact with diverse species in "hot spots" (Cohen, 2000; Weiss and McMichael, 2004; Jones et al. 2008). EID gain a foothold in these "hot spots" where poverty, poor sanitation and inadequate healthcare increase the risks to people vulnerable to an outbreak (Weiss and McMichael, 2004; Jones et al. 2008). Increased mobility from air travel and globalization allows pathogens to spread across the globe, implying that local risks are now global and exogenous to other nations (Cohen, 2000). In response policymakers have been encouraged to intervene to prevent new outbreaks (Cohen, 2000; Morse et al. 2012). Both the World Health Organization (WHO) and CDC track emerging diseases and focus on developing and implementing strategies for prevention and control (Cohen, 2000; Smith et al. 2003). This increasing threat from pathogens and improvements in epidemiological understanding has made prevention a vital strategy to counter these exogenous changes in risk. Investment in prevention is a costly strategy with uncertain benefits, and the trade-offs involved in combating an EID are important considerations for policymakers.

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Herein we examine the optimal prevention for an EID with increasing exogenous risk for which there is no immunity, consistent with most emerging infectious diseases being zoonotic viruses (Taylor et al. 2001). We follow the approach of Reed and Heras (1992) (c.f., Kamien and Schwartz, 1971) to reformulate a stochastic optimal control problem involving the random outbreak of a pathogen as a deterministic, infinite horizon problem.[3] We include a hazard rate for the introduction of an EID, which is increasing because of exogenous factors and can be mitigated by investment in prevention. We then provide both a formal analysis and phase plane analysis. We include a numerical example where an influenza pandemic threatens to cause lasting damages of 0.6% of GDP[4] and can have lasting impacts due to changes in population characteristics (Meltzer et al. 1999; Almond, 2006; McKibbin and Sidorenko, 2007). Our phase plane analysis includes solving numerically for the path of prevention. We also perform a comparative dynamic analysis.

In doing so our approach extends the previous literature, which has assumed *constant* background risk over time. The only prior work to examine the random introduction of a pathogen is Horan and Fenichel (2007),[5] who examine a wildlife-livestock system and implicitly assume constant background risk. Tsur and Withagen (2013) include an exogenously changing background risk when considering how a country or region responds to climate change. They focus on the decision to invest in adaptation capital that reduces ex post damages, but exclude investment in prevention because it is assumed impossible in the context of their problem. The problem of sudden stochastic regime change due to environmental degradation has also received a lot of attention[6]. This prior literature has assumed a constant background risk. This is due to the nature of the problems they examine. In these models the hazard rate is driven by stocks of pollution or environmental degradation which are controlled by policymakers. The hazard rate when considering EID is driven by changes in a wide subset of climatic, ecological, and human factors over which policy makers have little influence, but that drive disease emergence and spread (Cohen, 2000; Jones et al. 2008).

A key contribution in our paper is that we allow these exogenous changes in background risk to increase the risk of pandemic over time when exploring the endogenous management of infection risk. Our results suggest that prevention expenditures are relatively small in comparison to the potential losses, and these expenditures need to be flexible and responsive to changes in background risk. We focus on "prevention capital" which in this context consists of investments in surveillance, monitoring, research and infrastructure that can be used to prevent a pandemic. These investments could include surveillance to prevent the spread of an EID. Early detection allows quarantine measures and travel restrictions to be employed to prevent further spread, and time to prepare vaccinations that prevent endemic levels of the disease. These actions require infrastructure and knowledge that can be considered a capital stock, and depend on background risk. The stock requires investment over time as it depreciates due to the evolution of pathogens and vectors of spread. Investments overtime may also be required to identify new disease threats and to maintain capacity in hotspots where EIDs are the most likely to emerge. Failing to respond to increases in risk would leave society under protected and lower the expected value of future benefits as background risk increases. We find that an exogenous increase in risk makes it optimal to make large investments in prevention capital to build up a stock of prevention, similar to Tsur and Withagen's (2013) analysis of investments in adaptation. The build up of the prevention stock makes capital more effective at reducing the hazard rate, endogenizing the risk. We derive conditions for the schedule—not just the steady state—when it is optimal to invest in prevention. Because we solve for our paths numerically we provide estimates of the savings due to investing in prevention and estimates of the required investments in prevention.

2. Economic–epidemiological model of a disease outbreak

Consider a benevolent resource manager charged with managing the risk of a major disease outbreak. Here we simplify matters and partition time by the date of the outbreak at time τ, which is a random variable. The manager's investments in prevention can delay the outbreak by lowering the hazard faced by the system. Pre-outbreak, when $t<\tau$, there are no damages although costly investments in prevention help avoid or delay future damages. Following an outbreak, when $t \geq \tau$, realized damages have known intensity and duration, and are taken as given.

The probability of an outbreak at τ is represented using the Reed and Heras (1992)'s method, following Barbier (2013). If $G(t)$ is the probability that an outbreak has already occurred, then the probability an outbreak has not occurred is given by

[3] This approach has been applied to managing forests at risk of fire (Reed, 1984, 1987a, 1987b), fisheries at risk of collapse and other environmental applications (Reed and Heras, 1992), resources subject to a regime shift (Polasky et al. 2011), and resource collapse due to land conversion (Barbier, 2013).

[4] Depending on the severity of a pandemic, McKibbin and Sidorenko (2007) estimate that it would cause a 0.6–3% loss in GDP for the US. These estimates include investment in control and adaptation with estimates of how effective different countries would be able to deal with a pandemic. The losses are due to a decrease in the labor force, increased cost of doing business, shifts in consumer preferences and changes in investment risk.

[5] The ex post problem has received significant attention, (see Geoffard and Philipson, 1997; Goldman and Lightwood, 2002; Gersovitz and Hammer, 2003; Gersovitz and Hammer, 2005; Fenichel et al., 2010; Aadland et al., 2011; Rowthorn and Toxvaerd, 2012).

[6] The impact of endogenous versus exogenous risk on the optimal choice of prevention has been examined in detail (Tsur and Zemel, 2007; Polasky et al., 2011). Tsur and Zemel (2009) examine how the social discount rate is made endogenous by the threat of catastrophic climate change and the implications for control. Tsur and Zemel (2008) explore costate variables and derive Pigouvain taxes to reduce the hazard rate when the endogenous risk of a shift is related to a stock of an environmental bad. Kagan (2012) examines the impacts of climate change skepticism and finds that even when agents are nonresponsive to their impact on the probability of a regime shift, they will react to the risk if they expect some future change in benefits. The endogeneity of risk has been shown to matter when considering the tradeoff between investments in vaccination before and after an outbreak (Nævdal 2012), and between prevention and adaptation in managing the risks of climate change (De Zeeuw and Zemel, 2012; van der Ploeg and de Zeeuw, 2013).