Risk assessment and management of animal disease-related biosecurity

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Abstract: Animal agriculture is vulnerable to both intentional and unintentional biological threats. Outbreaks, especially intentional attacks, could cause enormous consequences extending well beyond agriculture. Nations, including the USA, are consolidating and coordinating efforts to protect against these biological threats. The efforts employed largely fall into the categories of ex ante prevention/preparedness and ex post response/recovery. The optimal mix across these strategies depends on the event probability, expected economic consequences, costs and effectiveness of strategies, and disease spread rates along with other factors. We review the literature discussing vulnerability and mitigation strategies and issues of relevance to agricultural security and then develop strategic recommendations based on economic analyses. These recommendations address (1) what categories of mitigation strategies are likely to be most effective (2) what implementation obstacles exist and how these implementation challenges could be managed or overcome and (3) what leverages can be done on technology, scientific advancement and education.

Keywords: agroterrorism; animal pathogens; biological threats; preparedness; prevention; recovery; response; risk assessment; risk management; vulnerability.

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1 Introduction

> "Perhaps the most important reason for the decline of ancient civilisations, however, was the spread of infectious diseases, most of which were caused by microbes that had spread to humans from domesticated animals" Torrey and Yolken (2005, p.140).

Agriculture and food supply is vulnerable to both intentional and unintentional biological threats (Brower and Chalk, 2003; Chalk, 2004; Cupp, Walker and Hillison, 2004; GAO, 2005; Crutchley et al., 2007). This article focuses on risk management for both intentional and unintentional introductions of animal pathogens and infectious diseases. We focus our attention on livestock-related threats because of the livestock industry's high vulnerability in terms of susceptibility to threats and potentially substantial economic losses. Livestock diseases can spread rapidly and widely as the industry routinely employs rapid, large scale geographic movements through many hands (Chalk, 2004; Cupp, Walker and Hillison, 2004; Crutchley et al., 2007). These movements provide multiple entry points for pathogens and facilitate disease spread. Intentional introductions of livestock diseases are likely to have even larger consequences than unintentional outbreaks and may cause political instability and public terror. Whitby (2002) indicates that historically countries developing biological warfare capability usually place lower priority on crop attacks than animal and human ones and that anti-crop attacks have been notably less successful. Plant events tend to have a longer time lag, months or even years, between introduction and outbreak (Madden and Wheelis, 2003) with diseases developing over a single or multiple growing seasons through pathogen multiplication (Campbell and Madden, 1990). For example, the citrus canker was present in Florida for almost three years before it was discovered (Schubert et al., 2001).

Potential bioterrorism options include microbes which have been known for thousands of years (e.g. smallpox, anthrax, brucellosis, Q fever, tularemia and glanders) as well as microbes which apparently have moved from animals to humans more recently (e.g. Ebola virus and Lassa virus; Torrey and Yolken, 2005, p.130).

2 Animal disease risk assessment: probability and consequences

2.1 Probability of animal pathogen-related threats

Many experts argue that the biological risks to agriculture are increasing (Chalk, 2004; Cupp, Walker and Hillison, 2004; Crutchley et al., 2007). Agricultural security is particularly vulnerable to animal pathogens because of the characteristics of the livestock industry and meat supply chain.

First, animal agriculture is highly concentrated. One example is the meatpacking industry in both the US and Canada. GIPSA (2007) shows that in 2005, the top four firms accounted for 67% of US animal slaughter. Canadian statistics indicate that the top four firms accounted for 79% of all animal slaughter and 62% of all poultry processing in 2001 (Harrison and Rule, 2004). In the UK, the top 10 slaughter plants account for approximately 37% of cattle slaughter, 44% of sheep and 60% of swine (Meat and Livestock Commission, 2006). Animal agriculture is also significantly concentrated geographically. Breeze (2004) estimates that 75% of the swine are raised in the Midwest, 90% of the broilers are in the Southeast and over 80% of the feedlot cattle are in the Midwest and Southwest. Canadian statistics show beef cattle are located predominantly in Alberta (48%) and Saskatchewan (21%), dairy cattle in Quebec (37%) and Ontario (36%), and poultry in Ontario (36%) (Beaulieu and Bédard, 2003). Geographic and industry concentration in the livestock industry increases the susceptibility to both intentional and unintentional biological threats (Cameron and Pate, 2001; Chalk, 2004; Cupp, Walker and Hillison, 2004; Crutchley et al., 2007).

Second, livestock and meat products routinely move across large geographic areas, passing through many hands (Chalk, 2004; Cupp, Walker and Hillison, 2004; Crutchley et al., 2007). For example, cattle auction surveys show 20–30% of US cattle move to locations at least 48 km away from the auction site, often crossing several states within 3–4 days (Chalk, 2004). Cupp, Walker and Hillison (2004) argue that on average US meat travels approximately 1,600 km from farm to table. The degree of movement provides numerous potential entry points for animal pathogen introduction and makes it possible to have wide-spread disease outbreaks. USDA modelling suggests that food-and-mouth disease (FMD) could spread to as many as 25 states in as few as five days facilitated by animal movement (Chalk, 2004).

Third, a lack of physical security and surveillance systems enhances vulnerability. Current control systems largely depend on farmer visual diagnosis and self-reporting (Kuchler and Hamm, 2000; NAO, 2002). This expands vulnerability in at least three major ways. First, since detection is based on visual observation of clinical signs, the disease could have been present and possibly spreading before discovery. Second, the clinical signs of some animal pathogens like FMD are indistinguishable from the signs of some other diseases (Bates et al., 2003; Elbakidze, 2007) and could be misidentified. Third, farmers often lack incentives to report infection. Kuchler and Hamm (2000) demonstrate that farmers reduce their efforts to identify infected livestock within their flocks as the indemnity payments decrease.

Furthermore, industry agents seldom prevent unauthorised access to animal holding areas, especially in the animal auctions, sale barns, ranches and smaller feedlots (Chalk, 2004; Crutchley et al., 2007). This is especially true in smaller operations. Pelzel, McCluskey and Scott (2006) suggest that the 2004 Texas avian influenza outbreak most likely was caused by unauthorised bird movement to and from a live bird market. Food processing and packing plants also tend to lack security and safety preparedness measures (Chalk, 2004; Crutchley et al., 2007).

Overall, with the increasing concentration of animal agriculture and food supply chain along with globalisation, the likelihood of having unintentional introduction of animal pathogen is increasing. Deliberate attacks can exploit these vulnerabilities (Casagrande, 2001; Chalk, 2004; Crutchley et al., 2007). But in spite of this vulnerability, intentional cases of livestock (or crop) infections have been rare. Chalk (2004) lists 12 cases where pathogenic agents were used to infect livestock or contaminate food produce. Only two cases were categorised as terrorist attacks: the 1984 Rajneeshee salmonella food poisoning in Oregon and the 1952 Mau Mau plant toxin incident in Kenya. Japan is the only country known to have used anti-agricultural weapons (Madden and Wheelis, 2003). Wilson et al. (2000) indicate that anthrax was spread by Rhodesian Security Forces to destroy African cattle between 1978 and 1980 and glanders was used by the Soviet Army in Afghanistan against horses. However, Kumagai (2006) argues that a biological attack on an agricultural target should be expected to become one of the most likely terrorist modes. Tommy Thompson, former Health and Human Services Secretary expressing concern about the US food supply attack during his resignation speech, said "I, for the life of me, cannot understand why terrorists have not attacked our food supply because it is so easy to do!" (Washington Post, 2004).

2.2 Consequences of animal pathogen-related threats

Animal pathogen introduction, whether intentional or unintentional, could cause substantial economic, social, political and public health disruptions.

Given the historical scarcity of intentional events, researchers need to estimate the extent to which consequences of intentional animal pathogen use would exceed the consequences of unintentional introductions of pathogens. It is most likely that intentional events, designed to cause maximum damage, will be more costly than random naturally occurring outbreaks. As shown in Pendell et al. (2007), simultaneous introduction in multiple production sites, a more likely scenario for an intentional attack, will be more costly than a single site introduction. In general, consequences can be divided into two broad groups: those associated with disease control and management and those associated with market and trade disruptions as discussed immediately below.

2.2.1 Costs associated with disease control and management

Should an animal disease outbreak occur, extensive costs associated with disease control and management are expected. The 1997 Taiwan FMD outbreak cost the pork industry $US15 billion in total (Blancou and Pearson, 2003), among which the cost for surveillance, cleaning and disinfection amounted to $US4 billion (Seebeck, 2007). NAO (2002) estimates that the UK government spent approximately £1.3 billion ($US2.6

billion) in controlling and eradicating the 2001 FMD outbreak. Cupp, Walker and Hillison (2004) estimate that the US 1983–1984 avian influenza outbreaks cost $US63 million and the 2002 case led to a producer loss of $US130–140 million.

Disease-related costs also include farmer compensation for livestock-related losses. In the 2001 UK FMD outbreak, this cost £1.4 billion ($US2.7 billion; NAO, 2002). Disease control and management measures such as quarantine zones and restricted movements can further increase business revenue losses (Breeze, 2004). NAO (2002) indicates that tourism and supporting industries suffered the largest financial impact in the 2001 UK FMD outbreak. Visitors were deterred by the movement ban and media images of mass carcass disposal pyres. Environmental costs also arise, including the value of lost wildlife plus environmental damages from disposal of contaminated carcasses (Sumner, Bervejillo and Jarvis, 2005).

2.2.2 Costs associated with market and trade disruptions

Burton and Young (1996) find that animal disease outbreaks reduce consumer confidence and decrease consumption of directly affected meat products. Immediately after the 1996 UK announcement of a possible link between bovine spongiform encephalopathy (BSE) and its human version, *vCJD*, sales of beef products decreased by 40% and household consumption decreased by 26% (Leeming and Tuner, 2004). McCluskey et al. (2005) find that Japanese beef consumption dropped by 70% immediately after the 2001 Japanese BSE discovery. Schlenker and Villa Boss (2008) find a beef sales reduction following the first US BSE discovery, but that the effect dissipated over three months. Atkinson (1999) found consumption effects differing for different cuts of beef with burgers and mince experiencing larger BSE induced effects than better cuts.

Outbreaks affect meat prices and change price margins along the supply chain and across products. Leeming and Turner (2004) report that during the 1995–1997 UK BSE outbreaks, cattle price fell by 21% while the price of sheep and pigs rose by 19–21%. Lloyd et al. (2001) indicate that UK beef prices at retail, wholesale and producer levels fell by 1.7, 2.25 and 3.0 pence per kilogram following the 1996 UK BSE discovery. Animal disease outbreaks may cause differential impacts along the supply chain, which changes the price margin (Sanjuan and Dawson, 2003; Park, Jin and Bessler, 2008; Lloyd et al., 2006). As a result, the relative profit at the farm, wholesale and retail levels will change as well.

Other studies have investigated the impact of food scares on stock, equity and futures prices. Henson and Mazzocchi (2002) found that the 1996 UK BSE discovery had a negative impact on stock prices of 24 UK companies. Schlenker and Villas-Boas (2006) find that the first US BSE discovery caused futures prices to drop compared with the estimated retail price change, but contracts with longer maturity had a smaller drop. Jin, Power and Elbakidze (2008) find that the 2002 Canadian and US BSE discoveries decreased US live cattle futures prices and increased the price volatility. The impacts were stronger and more persistent for nearby maturities than they were for more distant maturity futures.

Market distortions can be regional, national or even international. Following the 1996 UK BSE event, the European Union banned UK beef exports. The lost exports were worth about £600 million, plus there was a loss of £70 million in live calf value (Atkinson, 1999). Japan immediately stopped beef imports from the US after the 2003 US BSE case, which caused an export loss of $US1.7 billion (CIDRAP, 2005).

International trade regulations, per OIE (The Office International des Epizooties), restrict trade into FMD free countries from areas that have outbreaks of FMD and/or use vaccines (Breeze, 2004).

2.2.3 Additional or enhanced consequences of intentional introductions of animal pathogens

Unintentional animal disease outbreaks have caused market and trade disruptions associated with the affected and related commodities. With greater fear and terror resulting from a deliberate attack using animal pathogens, we envision even greater market consequences. A terrorist agent will exploit vulnerabilities, selecting animal pathogens that pose a national security risk, with easy dissemination, high degree of contagion and/or great potential to cause public fear and social disruption (Blancou and Pearson, 2003; Chalk, 2004; Cupp, Walker and Hillison, 2004). OIE lists FMD, Bluetongue, Rift Valley Fever, BSE and avian influenza as pathogens that can cause enormous economic and social consequences. Cupp, Walker and Hillison (2004) indicate that a terrorist agent is likely to introduce animal pathogen(s) at several critical points along the supply chain. Pendell et al. (2007) show that economic damages would be substantially higher if FMD outbreaks were started at five large feedlots simultaneously rather than at a single medium size feedlot or in a single cow–calf herd.

It is likely that intentional animal disease outbreaks will cause greater economic and social disruptions than unintentional outbreaks. Blancou and Pearson (2003) argue that even a declaration of deliberate infection would likely cause immediate and severe losses. For example, Cupp, Walker and Hillison (2004) indicate that a veterinarian, who noticed and reported possible signs of FMD disease in Kansas that turned out to be false 48 hours later, led to plummeting market prices for cattle futures and a loss estimated at $US50 million.

3 Animal disease risk management

Given the vulnerabilities of agriculture and the potentially enormous consequences of infectious animal disease outbreaks, especially of deliberate outbreaks, there is a need to improve security measures to make the exploitation of the vulnerabilities harder and to minimise the overall costs. We address three key issues associated with animal disease risk management:

1. Distinctions between *ex ante* and *ex post* strategies as well as identification of strategies that can be used both *ex ante* and *ex post.*
2. Balancing between *ex ante* and *ex post* strategies.
3. Implementation issues.

3.1 Potential ex ante and ex post strategies

The *ex ante* strategies include prevention, preparedness and investments in response capability, while the *ex post* strategies can be categorised into response and recovery activities. Some strategies such as surveillance and detection can be used both *ex ante* and *ex post*.

3.1.1 Ex ante strategies: prevention and preparedness

In general, *ex ante* strategies can be undertaken to reduce the probability of a successful biological threat and to reduce costs by enhancing the preparedness and response capacities. Prevention includes, but is not limited to, activities such as restricting access to biological agents, protecting critical points along the supply chain, increasing security measures and monitoring of products at facilities. The 2004 US Homeland Security Presidential Directive-9 mandated a number of prevention measures to defend the agriculture and food systems against both intentional and unintentional disease outbreaks. These included expanding disease surveillance and monitoring systems, continuing vulnerability assessments and developing a national veterinary stockpile. The first strategy can be also used as a response action. Further, activities undertaken to improve the forecast of the likelihood and consequences of events such as intelligence gathering are also a part of *ex ante* strategies.

Ex ante preparedness actions include investments in response capability/ infrastructure, action plan development and any other activities which would enhance society's preparedness. Adequate preparedness allows for timely response actions limiting disease spread and mitigating damages, plus it facilitates recovery. Potential preparedness investment activities include training of response personnel, stocking equipment for response, developing capability to identify, trace and destroy contaminated food and livestock, management of consequences including aiding the affected population, and so forth. For example, Becker (2005) argues that a key preparedness strategy against infectious animal disease outbreaks, the US National Animal ID System for the purpose of livestock disease tracking, which is currently based on voluntary participation by the producers, will ultimately need to have full compliance for the system to work effectively.

3.1.2 Ex post strategies: response and recovery

After proper identification of the pathogens and confirmation of animal disease outbreak, the immediate objective is to curb the disease spread and minimise consequences of the disease on agriculture and national economy. To achieve this objective, appropriate and timely response and recovery strategies are needed.

Response actions involve immediate implementation of the previously designed contingency plans such as diagnosis, disinfection, slaughter and destruction of infected animals, and so forth. Breeze (2004) outlines a likely scenario for US FMD outbreak response. A sample from the suspect animals will be sent to the Plum Island Foreign Animal Disease Diagnostic Laboratory. While the sample is being examined, the affected herd and others in the immediate vicinity or with recent contact will be strictly quarantined. Once the virus is confirmed, the affected herd as well as herds within a radius of up to 3 km and herds with direct contact will be killed. Authorities will keep on quarantining herds, restricting animal movements, slaughtering and disposal of diseased animals until the disease is eradicated.

Disposal of contaminated animal carcasses is a complex and key part of disease control and management requiring a substantial amount of *ex ante* preparation in terms of identifying disposal sites, methods and logistics. There are various technologies that may be employed to dispose of contaminated animal carcasses, including burial, incineration, composting, rendering, lactic acid fermentation, alkaline hydrolysis and anaerobic digestion (NABCC, 2004). The choice of disposal method largely depends on the event size, disposal capacity, cost and effectiveness along with other factors. Disposal facilities can be constructed and located before an outbreak occurs. However, such facilities can be expensive and typically have limited capacity. *Ex ante* establishment of massive disposal capacity may be difficult to justify given the infrequency of major outbreaks. Currently existing disposal capacities are likely to be inadequate for a massive slaughter and disposal of contaminated animals as evidenced by the UK 2001 FMD case (NAO, 2002).

Furthermore, when it comes to deliberate animal disease outbreaks, response actions also include capturing the perpetrators. When a zoonotic disease is introduced to animal agriculture, a special action for public health needs to be undertaken (Cupp, Walker and Hillison, 2004).

Recovery entails restoring the system to pre-event condition which requires rebuilding consumer confidence, resuming agricultural production and re-opening local, national and international businesses. Farmers whose livestock are depopulated will receive compensation (Kuchler and Hamm, 2000). Recovery issues also involve businesses caught in quarantine zones or affected by movement bans, farmers outside the affected areas who face market and trade disruptions, consumers who lost confidence in food safety, and trade embargos. Measures need to be undertaken to restore the public's confidence and support of the government. Restoring public confidence may be especially important in the case of a deliberate event. Not only do the perpetrators need to be captured and disarmed, but also the public needs to be convinced that the threat has been eliminated and no further attacks are expected.

Communication strategies are a key part of overall response and recovery strategies. Nayga, Aiew and Nichols (2005) argue that the media has two fundamental roles to play: informing the public about the incident and facilitating restoration of lost consumer confidence. There are many studies investigating public information related to health and food scares (Mazzocchi, 2006). Piggott and Marsh (2004) find that beef demand declined by 0.144% in response to 10% increase in publications with negative information. Some studies differentiate positive (reassuring the public about food safety) and negative (reporting consequences of adverse events) information. Smith, Raveswaay and Thompson (1988) find that negative media coverage dominates positive coverage, arguing that positive coverage following negative items failed to fully restore consumer confidence. In the case of deliberate outbreaks, it is even more important for the government to communicate with the public about consequences and measures undertaken (Chalk, 2004; Parker, 2005). In the absence of such communication, news and television coverage may potentially initiate chain reactions of destabilising socio-political events.

3.1.3 Strategies which can be employed both ex ante and ex post

Surveillance and detection is an example of the strategies that could be used both *ex ante* and *ex post*. A functional surveillance and detection system can identify and isolate infected animals and avoid disease spread. Early detection is the difference between an easily controllable outbreak and one that escalates out of control because of rapid disease transmission. The 2001 UK FMD outbreak escalated out of control largely because of the failure to identify infected sheep for more than a week, during which time the sheep were transported and the disease spread throughout the country (NAO, 2002). Accurate surveillance and detection is also a part of response strategy. Enhanced surveillance and detection, in the case of confirmed disease presence, allows earlier culling of infected herds to limit pathogen transmission and reduces unnecessary culling to reduce containment costs (Wheelis, Casagrande and Madden, 2002). We expect more frequent and extensive detection and surveillance when used as a response strategy than when used as a preventive strategy.

Vaccines are sometimes used to prevent and control animal diseases. Sumner, Bervejillo and Jarvis (2005) state that Uruguay, Argentina and Paraguay maintained FMD-free status with vaccination in some periods of the 1990s. Vaccination can play an important role as a response strategy. First, it can curb disease spread and decrease total event costs. Second, it can lessen pressure on the slaughter and disposal of contaminated animals. For example, during the course of the UK 2001 FMD outbreak, at the peak more than 400,000 animals were awaiting slaughter and more than 200,000 animals were awaiting disposal (NAO, 2002). This mass backlog suggests a potential value of vaccination as a response strategy, which slows down spread of disease while depopulation is underway. However, there are several issues associated with vaccination.

1 *Effectiveness*. Overall, effective vaccines exist against animal disease such as FMD, Newcastle disease, classical swine fever, highly pathogenic avian influenza, provided that they are produced with the appropriate serotype of the virus (Blancou and Pearson, 2003).

2 *Feasibility*. The feasibility of vaccination depends upon the availability of vaccines, timely delivery of vaccines to the affected areas, and number of available veterinarians at the local and national levels. In the case of FMD vaccines, besides conventional commercial FMD vaccine that has a 12 month shelf life, the North American Vaccine Bank (NAVB) and the European Pairbright Laboratory store and manage concentrated inactivated vaccines with a 15-year predicted shelf life (Doel and Pullen, 1990). A large scale vaccination imposes great pressure on vaccine reserves and may justify vaccine stocks as well. The second dimension of feasibility is whether vaccines can be delivered in a timely fashion to the infected and contact regions. Breeze (2004) argues in the US, it will take 1–2 days for preliminary diagnosis; 2 days to determine the virus subtype; 4 days to produce the vaccine and deliver it to the outbreak location and at least 1 day to administer the vaccine in the design area designated. This implies that it will take a minimum of 8–9 days to employ vaccination even if virus subtypes are available in NAVB. Last, a large number of animals needing to be vaccinated may impose pressure on veterinarians if vaccination is adopted.

3 *Trade implications*. Vaccination is not viewed as desirable in some diseases because of its trade implications. As stated in Breeze (2004), based on the technology of the 1980s, blood tests for FMD cannot distinguish between vaccinated animals and infected, but recovered animals that may be still infectious for long periods. International rules restrict exports from either FMD endemic countries or countries adopting vaccination to disease-free countries (Breeze, 2004; Sumner, Bervejillo and Jarvis, 2005). The trade disadvantage was the main reason for the Farmers Union opposition to vaccination during the 2001 FMD outbreak (NAO, 2002). However,

commercial tests developed by the USDA scientists in 1994 are able to distinguish between vaccinated animals and previously infected animals (Breeze, 2004). Given the technology advancement and the increasing biological threat to animals, there is a need to revisit the trade barrier associated with vaccination.

3.2 Resource allocation among strategies

Resource allocation between *ex ante* and *ex post* strategies as well as within each category is a complex issue as it depends on various factors such as disease type and spread rate, the probability and expected damages brought on by the event, the effectiveness, costs and co-benefits of *ex ante* and *ex post* mitigation strategies (Elbakidze and McCarl, 2006).

If we have sufficient information about all relevant factors, we can determine optimal resource allocation among prevention, preparedness, response and recovery measures subject to budget and technology constraints. Unfortunately, uncertainty abounds, particularly on the probabilities of alternative attack forms, the levels of damages and the effectiveness of the strategies in each of these strategy categories. While it is difficult to assess the probabilities of various types of events, it is relatively more feasible to evaluate relative effectiveness and costs of various mitigation strategies under various scenarios of disease outbreaks. Much research effort is needed to collect as much information as possible about economic effectiveness of mitigation strategies to arrive at informed decisions pertaining to allocation of resources between *ex ante* and *ex post* actions.

The resource allocation decisions need to reflect the endogeneity of risks (Barbier and Shogren, 2004). Endogenous risk models take into account that economic agents can affect the likelihood and consequences of events (Shogren, 2000). In the case of animal disease outbreak, prevention investment will reduce the likelihood of certain types of events, while investment in preparedness, response and recovery will reduce the severity of events. For example, timely detection and destruction of infected animals will reduce the chances of disease spread and thus decrease event costs. In the case of intentional introduction of animal pathogens, the endogenous risk issue becomes more complex in terms of prevention. Investments in preparedness will not just reduce severity, but can decrease the probability of events. The strategies and tactics of terrorists are dynamic and reflect rational adjustments in response to *ex ante* protection and preparedness strategies (Enders and Sandler, 1993). Also, while prevention strategies may be able to deter certain models of attacks they maybe ineffective overall due to terrorists' substitution to less protected targets.

An optimal strategy mix should also consider spillover and/or co-benefit effects of actions. Often, practices that control or prevent a given disease will also have value for other diseases. For example, periodic testing for FMD may also detect other diseases. Similarly, pre-installed facilities and trained personnel can be also used for other public health crises. Failure to consider co-benefits will lead to underestimation of biosecurity investment benefits (Wolf, 2005).

3.3 Implementation issues

A disease-free environment is a public good (Sumner, Bervejillo and Jarvis, 2005). Protecting the herd of one farmer also protects other nearby farmers (Sumner, Bervejillo and Jarvis, 2005; Wolf, 2005). Vaccination undertaken by certain livestock producers or their participation in an animal tracking system decreases the probability of infection for non-participating farmers (Elbakidze, 2007). Hence, some may ‘free ride’ at the expense of those who do participate in the programme. The existence of public good characteristics leads one to expect less than socially optimal mitigation investment (Hanley, Shogren and White, 1997; Sumner, Bervejillo and Jarvis, 2005; Jin and McCarl, 2006). The public good characteristics affect producer cooperation and participation in mitigation efforts unless appropriate incentives are in place. For example, an announcement that a particular region will be depopulated could lead to outgoing animal transportation which could contribute to spreading the disease. Although the existence of public good characteristics provides a rationale for public policy intervention in centralised control schemes to lower the risks of disease prevalence (Bicknell, Wilen and Howitt, 1999), such characteristics do not preclude private activities nor do they determine precisely the appropriate form of government action (Sumner, Bervejillo and Jarvis, 2005; Jin and McCarl, 2006). Overall, incentive mechanisms are warranted to induce individual farmers’ *ex ante* investment in prevention/preparedness, periodic testing and animal traceability. Incentive mechanisms are also needed to enhance producer’s willingness to participate in *ex post* response and recovery activities. Mechanisms like financial compensations for slaughtered/infected animals need to be designed carefully to avoid under reporting or over reporting.

4 Recommendations

Based on the literature and aspects of the economic and risk issues discussed above, we provide some recommendations on determining optimal mitigation strategies, overcoming implementation challenges, and leveraging technology, scientific advances, and education.

4.1 What categories of mitigation strategies are likely to be more economically effective?

The optimal combination of best strategies has been shown to be disease, location, context and time specific. Thus, definite answers cannot be provided on the optimal set of mitigation strategies across the total disease spectrum. Furthermore, the strategy mix also depends on probabilities, severities of events, costs and effectiveness of various mitigation strategies among other factors. Motivated by Elbakidze and McCarl (2006), we present economic analysis along with risk management that helps to generate some insights on the optimal balance between various *ex ante* irreversible investments and *ex post* response and recovery expenditures as well as the optimal expenditure allocation among various *ex post* strategies upon the confirmation of disease outbreak. In general, *ex ante* investment is more desirable if

1. The probability of disease outbreak increases – that could be either suggested by credible intelligence information of potential deliberated attacks or predicted by comparative analyses between the current condition and the condition under which unintentional disease outbreak occurs. Certainly avian influenza, FMD and BSE warrant attention given recent world history.

2 The disease is more contagious and transmits faster – this weighs in favour of FMD protection and against BSE. Perhaps it also weighs against avian influenza in large poultry operations given the tight biosecurity and likely rapid containment.

3 The *ex post* response strategy is less effective or more costly – this would be true for FMD against BSE as the ability for the disease to go endemic in wildlife is a real possibility, but not for a disease like BSE.

4 The target is more valuable and could cause more substantial damages, perhaps with human health implications, which raises the relative desirability of BSE and avian influenza prevention.

Furthermore, there are a number of other factors that may be less disease specific. Given our knowledge and insight, the *ex ante* prevention investment is more desirable than the *ex post investment* if

1 the *ex ante* prevention investment is less costly and/or more effective

2 the *ex ante* prevention and preparedness measures have greater co-benefits

3 the public is risk averse. In general, a more risk averse community will tend to invest more in *ex ante* activities while a less risk averse community will tend to rely more on *ex post* response and recovery actions.

More generally, the economic balance framework provides a method for a case by case examination of investment tipping points in terms of event probabilities, above which *ex ante* investments are desirable.

It is apparent that in order to make well informed decisions pertaining to resource allocation between *ex ante* and *ex post* activities, research efforts are needed to better assess susceptibility of various agricultural targets; operational effectiveness, overall costs, and overall benefits of mitigation strategies; implementation obstacles for available mitigation options and ways to overcome them and risk attitudes of the public. Given the need for substantial research in each of these areas, some specific recommendations can be provided to improve the preparedness for potential outbreaks.

4.2 What can be done to limit and/or overcome implementation challenges?

Revisit some trade barriers and policies. Vaccination is not viewed as a desirable option in the case of FMD outbreaks because of the associated trade barriers as discussed above. However, the technology advancement has already made it possible to distinguish between the vaccinated animals and previously infected, but recovered ones (Breeze, 2004). Countries shall revisit the trade barrier associated with vaccination. Second, animal disease outbreak is likely to be region-specific. One useful trade policy to limit the adverse impact on regions that are not infected, but may suffer from trade disruptions is to adopt regionalisation policy (Paarlberg, Seitzinger and Lee, 2007). It allows trade to proceed from disease-free regions given those regions can certify/confirm the disease-free status. Regionalisation could be also beneficial to countries which import livestock and/or meat products from the disease-prevalent country as they face a less severe supply shock when regionalisation is adopted.

Coordinate and cooperate mitigation efforts among various parties. First, multiple governmental agencies protect the nation against animal outbreaks, each formulating and designing their own strategies and procedures. The Hurricane Katrina experience urges a need of multiagency response guidelines developed prior to large scale outbreak occurrence. Such guidelines would outline the plan of response action which would integrate the actions of various agencies in a complementary manner to avoid redundancies and/or remove bureaucratic obstacles. Crutchley et al. (2007) suggest that success requires interagency cooperation and coordination and the guidance of integrating federal, state and local response placed *ex ante*. Upon notification of an outbreak, an integrated response and recovery effort by multiple agencies should be undertaken following the guidelines developed *ex ante.* Second, mitigation efforts need to be coordinated across regions (Paarlberg, Seitzinger and Lee, 2007). For example, Rich and Winter-Nelson (2007) argue that since some regions would gain more from vaccination than from stamping out, compensation mechanisms may be needed to make culling (a preferred strategy in the long run) acceptable across the entire multiregional zone. Third, participation and cooperation of private parties along the supply chain in preparedness and response is also a key component to success. Due to the public good characteristics of disease control and management, incentive compatible mechanisms are needed to encourage private investment in prevention activities (Jin and McCarl, 2006) and participation in response and recovery activities (Sumner, Bervejillo and Jarvis, 2005; Elbakidze, 2007). In particular, Jin and McCarl (2006) suggest differentiated compensation schemes for culled livestock depending on individual farmers' *ex ante* prevention investment. Becker (2005) states that concern of additional costs and the worry of liability and confidentiality of records is one of the main reasons for industry resistance in the case of the US national identification system. Several bills have called for explicitly shielding animal ID data from public access largely because of farmer concerns about

1 The liability they might bear when some type of an event occurred and the animals were traced back to a particular individuals.

2 Maintenance of their competitive position relative to other producers.

Communicate with the public. Parker (2005) addresses agroterrorism risk communication before, during and after an attack. *Ex ante* communication with the public is about the vulnerability of agriculture and protection strategies that have or will been undertaken. The *ex ante* communication with the public will also help build trust and support for the government. If a terrorist attack is realised, risk communication with the public is warranted on the consequences of the attack, the appropriateness of response and recovery actions, and the safety of the available food supply. Post attack, an appropriate assessment of communication strategy effectiveness is needed to help determine what worked, what did not work and what could be done better next time.

4.3 How can we leverage on technology, scientific advance and education?

A better diagnostic technology can enhance accurate detection of diseased animals before they are symptomatic and/or contagious (Cupp, Walker and Hillison, 2004) and assist in culling/depopulation of herds during the course of disease outbreaks (Wheelis, Casagrande and Madden, 2002). Besides enhancing accuracy and timing of detection, technology advances may also improve surveillance efficiency and decrease overall mitigation costs.

Farmers, veterinarians and agricultural extension agents should be educated and better prepared to identify exotic animal diseases (Wheelis, Casagrande and Madden, 2002). In particular, Cupp, Walker and Hillison (2004) suggest that veterinary college curricula and continuing education programmes should improve coverage of foreign animal diseases. When a large scale outbreak occurs, either intentional or unintentional, teams of specialists will be deployed to assist in the diagnosis, containment and eradication of the disease. However, most countries lack such specialists when facing a multifocal, highly contagious disease outbreak, which makes international deployment of such specialists beneficial. The internationally deployed specialists can also gain valuable experiences in the diagnosis and control of non-endemic infectious diseases (Wheelis, Casagrande and Madden, 2002).

Besides epidemiologic and veterinary knowledge, education on economic principles associated with formation of mitigation strategies is also needed. Especially, policy makers and decision-makers in charge of agencies which take part in mitigation efforts need to be trained in economic analysis of mitigation strategies. Allocation of efforts and resources across *ex ante* prevention/preparedness and *ex post* response/recovery ought to be structured based on sound understanding of tradeoffs and challenges in light of uncertainties and conflicting interests.

5 Conclusions

Animal agriculture is vulnerable to both intentional and unintentional introductions of animal pathogens. An accidental animal disease outbreak could cause large economic damages with significant market and trade disruptions. An intentional introduction could result in political instability and public fear in addition to even more substantial economic consequences than under an unintentional outbreak. These consequences could be local, national or even international. Nations, including the US, are consolidating and coordinating efforts and strategies. These efforts largely involve *ex ante* prevention and preparedness as well as *ex post* response and recovery activities. The optimal strategy mix among these efforts depends on the event probability, expected economic damages, costs and benefits of strategy implementation, and value of animal targets among other factors. While specific scenario-based data will determine an optimal combination of strategies to be used on a case by case basis, the general framework of decision-making needs to be consistent with economic and risk-related principles. Implementation of *ex ante* and *ex post* strategies need to be based on evaluation and consideration of uncertainties pertaining to probabilities, potential damages, effectiveness, costs and feasibility of available mitigation options.

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References

Atkinson, N. (1999) 'The Impact of BSE on the UK economy', *Argentine Scientific Advisory Committee on Bovine Spongiform Encephalopathy (3rd Meeting)*, August. Available at: http://www.iica.org.ar/Bse/14-%20Atkinson.html (last accessed on August 6, 2007).

Barbier, E.B. and Shogren, J.F. (2004) 'Growth with endogenous risk of biological invasion', *Economic Inquiry,* Vol. 117, pp.19–36.

Bates, T., Thurmond, M., Hietala, S., Venkatesvaran, K., Wilson, T., Colston, B., Jr., Trebes, J. and Milanovich, F. (2003) 'Surveillance for detection of foot-and-mouth disease', *Commentary in Journal of the American Veterinary Medical Association*, Vol. 223, pp.609–614.

Beaulieu, M.S. and Bédard, F. (2003) 'A geographic profile of Canadian livestock, 1991–2001', *Statistics Canada, Agricultural Division, Working Paper No. 62*. Available at: http://www.competitioncommission.org.uk/inquiries/ref2006/grocery/pdf/third_party_submissions_ngo_cha_org_mlc.pdf (last accessed on April 11, 2008).

Becker, G.S. (2005) 'Animal identification and meat traceability', *Congressional Research Service Report for Congress, The Library of Congress, RL32012*. Available at: http://digital.library.unt.edu/govdocs/crs/permalink/meta-crs-8899:1 (last accessed in April 2008).

Bicknell, K., Wilen, J. and Howitt, R. (1999) 'Public policy and private incentives for livestock disease control', *Australian Journal of Agricultural and Resource Economics*, Vol. 43, pp.501–521.

Blancou, J. and Pearson, J.E. (2003) 'Bioterrorism and infectious animal diseases', *Comparative Immunology, Microbiology and Infectious Diseases*, Vol. 26, pp.431–443.

Breeze, R. (2004) 'Agroterrrorism: betting far more than the farm', *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, Vol. 2, pp.251–264.

Brower, J. and Chalk, P. (2003) The Global Threat of New and Re-emerging Infectious Diseases: Reconciling U.S. National Security and Public Health Policy. Rand, Santa Monica.

Burton, M. and Young, T. (1996) 'The impact of BSE on the demand for beef and other meats in Great Britain', *Applied Economics*, Vol. 28, pp.687–693.

Cameron, G. and Pate, J. (2001) 'Covert biological weapons attacks against agricultural targets: assessing the impacts against U.S. agriculture', *Terrorism and Political Violence*, Vol. 13, pp.61–82.

Campbell, C. and Madden, L. (1990) *Introduction to Plant Disease Epidemiology*. New York, NY: Wiley.

Casagrande, R. (2001) 'Terrorism on the hoof: livestock as a bioterrorism target', *Agrichemical and Environmental News*, Vol. 187, pp.8–9.

Chalk, P. (2004) 'Hitting American's soft underbelly: the potential threat of deliberate biological attacks against the U.S. agricultural and food industry', RAND, MG-135-OSD.

CIDRAP (Center for Infectious Disease Research and Policy) (2005) *Japan Ends BSE-Related Ban on US Beef.* CIDRAP News, December 12, 2005. Available at: http://www.cidrapforum.org/cidrap/content/other/bse/news/dec1205beef.html (last accessed on April 11, 2008).

Crutchley, T.M., Rodgers, J., Whiteside, H., Vanier, M. and Terndrup, T. (2007) 'Agroterrorism: Where are we in ongoing war on terrorism?', *Journal of Food Protection*, Vol. 70, pp.791–804.

Cupp, O.S., Walker, D.E. and Hillison, J. (2004) 'Agroterrorism in the U.S.: key security challenges for the 21st century', *Bioseurity and Bioterrorism*, Vol. 2, pp.97–105.

Doel, T.R. and Pullen, L. (1990) 'International bank for food-and-mouth disease vaccine: stability studies with virus concentrates and vaccines prepared from them', *Vaccine*, Vol. 8, pp.473–478.

Doel, T.R., Williams, L. and Barnett, P.V. (1994) 'Emergency vaccination against foot-and-mouth disease. the rate of development of immunity and its implications for the carrier state', *Vaccine*, Vol. 12, pp.592–600.

Elbakidze, L. (2007) 'Economic benefits of animal tracing in the cattle production sector', *Journal of Agricultural and Resource Economics,* Vol. 32, pp.169–180.

Elbakidze, L. and McCarl, B.A. (2006) 'Animal disease pre event preparedness versus post event response: when is it economic to protect?', *Journal of Agricultural and Applied Economics*, Vol. 38, pp.327–336.

Enders, W. and Sandler, T. (1993) 'The effectiveness of antiterrorism policies: a vector-autoregression-intervention analysis', *American Political Science Review*, Vol. 87, pp.829–844.

GAO (General Accounting Office) (2005) *Homeland Security: Much is Being Done to Protect Agriculture from a Terrorist Attack but Important Challenges Remain*. Available at: http://www.gao.gov/new.items/d05214.pdf (last accessed on April 11, 2008).

GIPSA (Grain Inspection, Packers and Stockyard Administration) (2007) 'Packers and stockyards statistical report, 2005 reporting year', *GIPSA, USDA*. Available at: http://archive.gipsa.usda.gov/pubs/2005_stat_report.pdf (accessed on April 11, 2008).

Hanley, N., Shogren, J.F. and White, B. (1997) *Environmental Economics: In Theory and Practice*. New York, NY: Oxford University Press.

Harrison, D. and Rude, J. (2004) 'Measuring industry concentration in Canada's food processing sectors', *Statistics Canada, Agricultural Division, Research paper No. 70*. Available at: http://dsp-psd.pwgsc.gc.ca/Collection/Statcan/21-601-MIE/21-601-MIE2004070.pdf (last accessed on April 11, 2008).

Henson, S. and Mazzocchi, M. (2002) 'Impact of bovine spongiform encephalopathy on agribusiness in the United Kingdom: results of an event study of equity prices', *American Journal of Agricultural Economics*, Vol. 84, pp.370–386.

Jin, Y.H., Power, G.J. and Elbakidze, L. (2008) 'The impact of North American BSE events on live cattle futures prices', *American Journal of Agricultural Economics*, Vol. 90, pp.1279–1286.

Jin, Y.H. and McCarl, B.A. (2006) 'Animal disease related pre-event investment and post-event compensation: a multi-agent problem', *Selected Paper at the Annual Meeting of American Agricultural Economics Association Annual, July, 2006*. Available at: http://ageconsearch.umn.edu/handle/123456789/14615 (last accessed on April 11, 2008).

Kuchler, F. and Hamm, S. (2000) 'Animal disease incidence and indemnity eradication programs', *Agricultural Economics*, Vol. 22, pp.299–308.

Kumagai, J. (2006) 'Nice cautionary tales', *Spectrum, IEEE*, Vol. 43, pp.36–45.

Leeming, J. and Turner, P. (2004) 'The BSE crisis and the price of red meat in the UK', *Applied Economics*, Vol. 36, pp.1825–1829.

Lloyd, T., McCorriston, S.M., Morgan, C.W. and Rayner, A.J. (2001) 'The impact of food scares on price adjustments in the UK beef market', *Agricultural Economics*, Vol. 25, pp.347–357.

Lloyd, T.A., McCorriston, S.M., Morgan, C.W. and Rayner, A.J. (2006) 'Food scares, market power and price transmission: the UK BSE crisis', *European Review of Agricultural Economics*, Vol. 33, pp.347–357.

Madden, L.V. and Wheelis, M. (2003) 'The threat of plant pathogens as weapons against U.S. crops', *Annual Review of Phytopathology*, Vol. 41, pp.155–176.

Mazzocchi, M. (2006) 'No news is good news: stochastic parameters versus media coverage indices in demand models after food scares', *American Journal of Agricultural Economics*, Vol. 88, pp.727–749.

McCluskey, J.J., Grimsrud, K.M., Ouchi, H. and Wahl, T.I. (2005) 'Bovine spongiform encephalopathy in Japan: consumers' food safety perceptions and willingness to pay for tested beef', *Australian Journal of Agricultural and Resource Economics*, Vol. 49, pp.197–209.

Meat and Livestock Commission (2006) *Investigation into the Supply of Groceries by Retailers in the United Kingdom*. Available at: http://www.competition-commission.org.uk/inquiries/ref2006/grocery/pdf/third_party_submissions_ngo_cha_org_mlc.pdf (last accessed on April 11, 2008).

NABCC (National Agricultural Bio-security Center Consortium) (2004) 'Carcass disposal: a comprehensive review (NABCC)', Prepared by the National Agricultural Bio-security Center Consortium at Kansas State University, Carcass Disposal Working Group for the USDA Animal and Plant Health Inspection Service per Cooperative Agreement 02-1001-0355. Available at: http://fss.kstate.edu/research/books/carcassdispfiles/Carcass%20Disposal.html (last accessed on April 2008).

NAO (National Audit Office) (2002) 'The 2001 outbreak of foot and mouth disease', *Comptroller and Auditor General, HC 939 Session 2001–2002: 21 June 2002*. Available at: http://nao.org.uk/publications/nao_reports/01-02/0102939.pdf (last accessed April 2008).

Nayga, R.M., Aiew, W. and Nichols, J. (2005) 'Information effects on consumers' willingness to purchase irradiated food products', *Review of Agricultural Economics*, Vol. 27, pp.37–48.

Paarlberg, P.L., Seitzinger, A.H. and Lee, J.G. (2007) 'Economic impacts of regionalization of highly pathogenic, avian influenza outbreak in the United States', *Journal of Agricultural and Applied Economics*, Vol. 2, pp.325–333.

Park, M, Jin, Y.H. and Bessler, D.A. (2008) 'The impacts of animal disease crises on the Korean meat market', *Agricultural Economics*, Vol. 39, pp.183–195.

Parker, L. (2005) *Agroterrorism Risk Communication: Challenges and Implications for Communicators, Naval Postgraduate School*. Available at: http://www.terrorisminfo.mipt.org/pdf/NPS-Thesis-Agroterrorism-Risk-Communication.pdf (accessed on March 21, 2008).

Pelzel, A.M., McCluskey, B.J. and Scott, A.E. (2006) 'Review of the highly pathogenic avian influenza outbreak in Texas, 2004', *Journal of the American Veterinary Medical Association*, Vol. 228, pp.1869–1875.

Pendell, D.L., Leatherman, J., Schroeder, T.C. and Alward, G.S. (2007) 'The economics impacts of a foot-and-mouth disease outbreak: a regional analysis', *Journal of Agricultural and Applied Economics*, Vol. 39, pp.19–33.

Piggott, N.E. and Marsh, T. (2004) 'Does food safety information impact U.S. meat demand?', *American Journal of Agricultural Economics*, Vol. 86, pp.154–174.

Rich, K.M. and Winter-Nelson, A. (2007) 'An integrated epidemiological-economic analysis of foot-and-mouth disease: application to the southern cone of South America', *American Journal of Agricultural and Applied Economics*, Vol. 89, pp.682–697.

Sanjuan, A.I. and Dawson, P.J. (2003) 'Price transmission, BSE and structural breaks in the UK meat sector', *European Review of Agricultural Economics*, Vol. 30, pp.155–172.

Schlenker, W. and Villas-Boas, S.B. (2008) 'Consumer and market response to mad-cow disease', *GUDARE Working Paper 1023*. Berkeley: Agricultural Economics, University of California.

Schubert, T., Rizvi, S., Sun, X., Gottwald, T., Graham, J. and Dixon, W. (2001) 'Meeting the challenge of eradicating citrus canker in Florida again', *Plant Diseases*, Vol. 85, pp.340–356.

Seebeck, L. (2007) 'Responding to systemic crisis: the case of agroterrorism', *Studies in Conflict and Terrorism*, Vol. 30, pp.691–721.

Shogren, J.F. (2000) 'Risk-reduction strategies against the `explosive invader', in C. Perrings, M. Willliamson and S. Dalmazzone (Eds), *The Economics of Biological Invasions*. Northampton, MA: Edward Elgar, pp.56–69.

Smith, M.E., Raveswaay, E.O. and Thompson, S.R. (1988) 'Sales loss determination in food contamination incidents: an application to milk bans in Hawaii', *American Journal of Agricultural Economics*, Vol. 70, pp.513–420.

Sumner, D., Bervejillo, J. and Jarvis, L. (2005) 'Public policy, invasive species and animal disease management', *International Food and Agribusiness Management Review*, Vol. 8, pp.78–97.

Torrey, E.F. and Yolken, R.H. (2005) *Beasts of the Earth: Animals, Humans, and Disease*. New Brunswick, New Jersey, NJ: Rutgers University Press.

Washington Post (2004) *Tommy Thompson Resigns from HHS*. December 3, 2004. Available at: http://www.washingtonpost.com/wp-dyn/articles/A31377-2004Dec3.html (last accessed on April 11 2008).

Wheelis, M., Casagrande, R. and Madden, L.V. (2002) 'Biological attack on agricultural: low-tech, high-impact bioterrorism', *Bioscience*, Vol. 7, pp.569–576.

Whitby, S.M. (2002) *Biological Warfare against Crops*. Hampshire, UK: Palgrave.

Wilson, T.M., Logan-Henfrey, L., Weller, R. and Kellman, B. (2000) 'A review of agroterrorism, biological crimes, and biological warfare targeting animal agriculture', in C. Brown and C. Bolin (Eds), *Emerging Disease of Animals*. Washington, DC: ASM Press.

Wolf, C. (2005) 'Producer livestock disease management incentives and decisions', *International Food and Agribusiness Management Review*, Vol. 8, pp.47–61.