The Economic Impact of High Consequence Zoonotic Pathogens: Why Preparing for these is a Wicked Problem

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Abstract: This paper reviews literature on the economic impacts of outbreaks and control strategies for high consequence zoonotic priority diseases, ie. zoonotic diseases that are generally FADs, zoonotic diseases that occur rarely, or zoonotic diseases that have bioterrorist potential sufficient to be important for the United States. Such diseases are referred to here as zoonotic priority diseases (ZPDs).

These ZPDs are categorized into three levels of economic impact: high, moderate, and low with the recognition that there are aspects of each of these diseases that could make the categorization presented here inaccurate. Arguments are made for why determination of optimal ZPD and more generally FAD preparedness and response strategies are wicked problems. The paper concludes with the implications for further development of appropriate ZPD policy and some needs for further analyses.

Keywords: Foreign animal disease, review, zoonotic, economics, international trade.

REVIEW OF THE LITERATURE

This paper reviews literature on the economic impacts of outbreaks and control strategies for high consequence zoonotic priority diseases, ie. zoonotic diseases that are generally FADs, zoonotic diseases that occur rarely, or zoonotic diseases that have bioterrorist potential sufficient to be important for the United States. Such diseases are referred to here as zoonotic priority diseases (ZPDs). ZPDs reviewed do not include diseases that are regularly occurring foodborne illnesses, such as those caused by Salmonella or E. coli, nor does it include zoonotic diseases which are regularly occurring and endemic program diseases, such as tuberculosis or brucellosis. Rather they are those diseases that USDA previously designated as important threats related to Homeland Security Presidential Directive 9 (HSPD-9). This review provides information about the economic consequences of disease occurrences, including the consequences to the affected industries. These are most often industries represented by a particular group of meat commodities, such as poultry. The paper also covers aspects that relate to components in the food chain, e.g. at processing and retail levels. Some of the details of the human health aspects of the disease are also provided to convey the potential human health associated costs. References of outbreaks from countries other than the United States are included if there is contrasting and useful information.

These diseases are categorized into three levels of economic impact: high, moderate, and low. Categories are a reflection of current U.S. circumstances and may change over time. Categorization of these same diseases could be very different in other countries than are reflected here for the U.S. Also, there is recognition that aspects of each of these diseases could make the categorization presented here inaccurate such that a low consequence disease occurs and the economic and social consequences are indeed quite high. This can occur when a pathogen that has zoonotic potential crosses over into humans when that does not normally occur, even though there is the potential for it to happen.

There is information about aspects of the methods used in eradication or disease exclusion. This information is presented when it is useful in order to understand better the economic implications of the disease.

Once there is a basic understanding of the potential economic impact of a zoonotic disease incursion, it becomes important to examine the costs and benefits of the various prevention and control strategies. Additionally, there are times when there is no need for detailed economic impact estimates, but rather a broad recognition of the extremely serious nature of the impact of a particular disease, and an agreement that the disease should be excluded from entering or eradicated as quickly as possible should it be introduced into a country. Nonetheless, in these circumstances, cost effectiveness analyses can be applied to examine what aspects are best to pursue for

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an exclusion or eradication program (Rich, Miller and Winter-Nelson 2005). There are a variety of different types of economic analyses that can be applied to gain perspective on how to proceed with different zoonotic priority diseases. Many examples are provided in this review.

The Highest Consequence Zoonotic Priority Disease Pathogens

Highly Pathogenic Avian Influenza

Beach *et al.* (2008) studied consumer response to HPAI news surrounding an H5N1 HPAI outbreak in Italy. They examined consumer grocery/market scanner data from October 2004 to October 2006 and showed that sales fell to 79.8%, 95.9%, and 85.4% of historic averages for fresh, frozen and processed poultry respectively. Consumer purchases declined the most directly following major news announcements.

Poultry industries as well as governments have experienced substantial economic consequences due to HPAI outbreaks. A major outbreak of HPAI and the first to occur in the U.S. since 1929 happened in 1983-84 and involved birds in the states of MD, NJ, PA, and VA (Lasley, Short, and Hensen 1985). Over 17 million birds were depopulated to eradicate the disease. The economic costs in 2010 dollars included: $89.8 million in indemnity payments, other government cost of $41.6 million (for salaries, transportation, rent, etc), producer direct losses of $118 million, and increased consumer expenditures for meats of $755 million. Had the HPAI outbreak not been contained, it was estimated that producer losses in 2010 dollars of $741 million for producers and $8.1 billion for consumers would have been incurred. Therefore, from a consumer and producer perspective, it was beneficial to contain the outbreak.

In 2004, British Columbia, Canada had an active outbreak time of 91 days with 51 days of formal downtime and 18 months of extended downtime and recovery. While there is no agreed upon definition of downtime, it generally refers to a period in which animals are not allowed to return to a depopulated premises; it can also refer to a period when the overall population in a farm or area/region is decreased because of a governmental requirement to not repopulate a farm or a region. This outbreak involved the depopulation of 410 infected and at risk test-negative commercial poultry farms and 553 smaller flocks that were close to infected premises. Ultimately, 90% of the commercial poultry farms in the Fraser Valley were depopulated. In total, just as for the U.S. outbreak, more than 17 million birds were culled (Bowes 2007). The economic consequences of this outbreak included unemployment or underemployment of an estimated 1,700 people, downstream uncompensated losses estimated at $156 million (unemployment), $63.7 million in indemnities paid for test-positive birds, $63.3 million in out-of-pocket costs for farms and processors, and a total gross economic cost of $380 million. Other unspecified costs included 86% of farm tax payments being late and renegotiation of many farm loans. No estimates were made for consumer costs or government expenses other than indemnities paid.

Models of the economic impacts of an HPAI outbreak in the U.S. include one by Paarlberg *et al.* (2007). They estimated that a regionalized outbreak in the U.S. would cost the poultry meat and egg sectors between $602 and $853 million over the first 16 quarters following the outbreak. Additionally, consumers would lose an estimated $900 million in consumer surplus because of higher prices and decreased consumption of poultry meats and eggs. In another model of the economic consequences of an outbreak, Brown *et al.* used the Food and Agricultural Policy Research Institute model (Brown *et al.* 2007). They predicted large declines in chicken production (a decline of 8.8 billion pounds from a baseline of 36.2 billion), and price increases of $0.11 per pound for broilers, $0.19 per pound for turkey, and $0.19 per dozen for eggs from baselines of $0.69, $0.74, and $0.82 respectively.

As an illustration of the potentially devastating effects of even a very small HPAI outbreak, in 2004, U.S. poultry exports were shut off from at least 44 countries because of an HPAI outbreak involving only the index farm and two live bird markets in TX (Pelzel McCluskey and Scott 2006). These 44 countries imposed import restrictions and maintained bans on imports until August 2005 even though the outbreak was relatively small and short; initial diagnosis was on Feb 16, 2004, and the 3 infected premises identified were depopulated within 6 days of the first laboratory confirmed case. The subsequent four week intensive surveillance program found all samples collected to be negative. Despite the small size of the outbreak, trading partner response was extensive. While this study did not report economic impacts per se, it is obvious that being ostracized from disease free world markets is costly. Fear of this type of world response underlies many attitudes in the agricultural production industries and USDA generally about ZPD response.

Djunaidi and Djunaidi (2007) modeled simultaneous outbreaks of HPAI in several countries. They found global export prices increased almost 10%. They also found large single country effects from outbreaks in the U.S. and Brazil.

Midlevel Consequence Zoonotic Priority Disease Pathogens

Diseases in this category include RVF, JE, VEE, and EEE. They are considered to be of relatively low likelihood of occurrence, to be more controllable than other ZPDs, or to have limited information available about the likely economic impacts. However, since these diseases are zoonotic, if an outbreak occurred in the U.S. and if humans were infected, the economic and social impacts could escalate the outbreak costs to potentially very large amounts. A small number of human deaths or health impacts can cause an outbreak to exceed in cost a relatively large disease outbreak that only involves domestic animals or wildlife. This is true if there is a value placed on the Disability Adjusted Life Years (DALYs) reported. Similarly, several of the following diseases are confined to impacts only in equines among domestic animals in the U.S.; to the degree that the disease escapes affecting very high value equine populations and does not affect humans, the impacts will likely be substantially smaller than FADs affecting multiple food production species.

The midlevel ZPDs are transmitted by hematophagous insects. The degree of competence of most vectors in North America is generally unknown. However, with increased global trade in addition to changing climates and increased temperatures in various places throughout the world, there are likely to be changes in the prevalence and locations of these pathogens (Dufour *et al.* 2008). This study used a two-phase approach to identify diseases with the potential for increased incidence or geographic distribution, and then to evaluate the risks of these diseases. They identified six priority diseases (bluetongue, West Nile Fever, visceral leishmaniasis, leptospirosis, RVF, and AHS) the latter two of which are included in this category of midlevel consequence pathogens. The main conclusions from this study were to recommend development of epidemiological surveillance, increased knowledge of the epidemiology of these diseases, and identification of better control methods which would include cross-border control strategies. These gaps in current knowledge hinder the economic analyses and estimated impacts of these midlevel ZPDs.

Rift Valley Fever

RVF is an FAD in the U.S. In other countries, it is sporadic in nature and occurs when climatic and environmental conditions are conducive. RVF is transmitted by several hematophagous arthropod species and mechanically by other biting arthropods or contact with the blood of viremic animals, infected viscera, aborted fetuses, and contaminated raw milk. It appears that many of the potential vectors in North America are not efficient vectors; of seven mosquito species tested, none were efficient vectors, but three did develop infections, and two were able to transmit RVF virus by bite (Turell *et al.* 2008). RVF does not spread person to person. Vaccination with live attenuated virus induces lifelong immunity but may cause spontaneous abortion in pregnant animals. A less robust antibody response is seen with killed virus vaccine and boosters are required annually (WHO 2010). A human vaccine has been developed by the Army Research Institute of Infectious Diseases that produces long-term immunity with two doses, but the vaccine is expensive and difficult to produce. Additional human and livestock vaccines are under development. Additional control measures include vector control (both larvicidal and adulticidal), movement control, livestock vaccination, and possibly antiviral use in humans (USAHA 2008).

RVF has been recognized as a high priority disease among several regional consultations that have identified diseases that jeopardize international trade (Domenech *et al*. 2006). Soumare *et al.* (2007) used interviews from 600 Somaliland livestock producers and 15 exporters to assess the socioeconomic effects of the ban on livestock imports imposed by Saudi Arabia during the RVF outbreaks in Somaliland. They estimated that between February 1998 and December 2003, the Somaliland government lost US$40 million from potential taxes on exported livestock and US$5 million from lost vessel docking fees. Livestock exporters lost US$330 million in profits and producers lost an additional estimated US$8 million annually. To provide a perspective on the importance of livestock exports to this country, export values during normal times represent an income estimated at US$150 million per year. As an example of the economic cost to producers, it was estimated that the export ban was associated with a decrease in price of 30% for young, weaned pigs. The living standards of producers who practiced farming other than livestock rearing suffered less than those who were pure pastoralists. Somaliland consumers gained US$94 million from the drop in livestock prices associated with the export ban. This study found substantial financial losses in general accrued to the normal beneficiaries of livestock trade, namely the government, producers and exporters.

Japanese Encephalitis

JE is transmitted primarily by *Culex* mosquitoes (USAHA 2008). JE causes clinical disease in horses, pigs, and humans.

There have been no studies (no studies were listed using standard library database searches) on the economic impact of JE in agricultural animals. The consequences of the disease in animals are limited mainly to reproductive failure in pigs and the negative impact on live animal trade (Ellis *et al.)*. It appears as though as many as 50% of cattle are exposed to JE in Korea, but the epidemiological role in cattle remains unclear because of uncertainties in the degree of viremia in cattle and the lack of sufficient circulating virus to infect mosquitoes (Lim *et al.* 2007).

Immunization of horses and swine in endemic areas is recommended (USAHA 2008). It is particularly important to vaccinate swine as they are amplifying hosts of JE. Control of vector populations helps decrease transmission in affected areas. However, were it to occur and become endemic in the U.S., it seems highly likely that control of JE would involve human immunizations given the experience in Asian countries.

In humans, JE is a public health problem in areas of East, Southeast and South Asia. In Japan, control measures applied include control of vector populations and mass human immunization (Igarashi 1992). Maha *et al.* (2009) documented the severity of JE by studying a cohort of children diagnosed with laboratory confirmed JE. They found that 50% of affected children died (25%) or had severe sequelae (25%) such that they would likely be dependent for life. The remaining children had mild to moderate illness (25%) or recovered (25%) fully. Tsai (2000) reported of the approximately 50,000 cases in China, Southeast Asian Countries and India, most cases were found in children.

A cost effectiveness study of vaccines found strong evidence to support the value of vaccinating people against JE in Shanghai (Ding *et al*. 2003). Compared to no vaccination, JE vaccination prevented 420-427 JE cases, 105-107 deaths, and saved 6,456-6,556 disability-adjusted life years (DALYs) per 100,000 people using the P3 or SA 14-14-2 vaccines respectively. The net cost savings associated with immunization per 100,000 people seems small (US$348,246-US$512,456 for PC and SA 14-14-2 respectively). This is in part explained by the low medical care costs in China (e.g. the total costs per case for acute care of JE illness was only US$1,209 (1997 US$) which encompassed inpatient care including a hospital bed, nursing and treatment (US$302), drugs (US$302), laboratory tests (US$242) and medical examinations (US$363)). Were JE to occur in the U.S., costs per case would be thousands to tens of thousands fold higher. Other studies have identified that there has been limited provision of JE vaccination in rural areas of China (Liu *et al*. 2006), although overall, the use of JE immunization has resulted in a marked decline (greater than 90%) of JE incidence in China. Additional secondary economic impacts that might be expected from this disease could include restrictions on tourism or recreational activities in areas near mosquito infested regions.

Venezuelan Equine Encephalitis

Control of VEE requires vector control in combination with equine vaccination. VEE antigen is commonly included in multivalent encephalitis vaccines for horses; consequently, most horses vaccinated for encephalitides in the U.S. are protected against VEE. Control of equine movement during outbreaks limits spread of VEE but is not sufficient by itself to end an outbreak (USAHA 2008). A vaccine for human use that was developed by the U.S. military has helped in equine epizootics of VEE, but not in human epidemics (Rico-Hesse 2000). No economic studies have been reported.

Eastern Equine Encephalitis

While rare in the U.S. with an average of 6 cases reported annually (CDC 2010), EEE is considered by some to be the most severe mosquito-borne encephalitic disease in the U.S. (Harvala *et al*. 2009). Indeed, among West Nile virus, California serogroup viruses, St. Louis encephalitis virus and EEE virus, EEE has the highest human case fatality rate (42%) (Reimann *et al*. 2008) and in some epidemics the case fatality rate has approached 70% (Dupuy and Reed 2012). Equine mortality may reach 100%. EEE is considered a persistent public health problem in the U.S. where 5-10 cases occur in humans annually and approximately 23 inapparent infections for each human case (Griffin 2008). The only treatment available for these infections is supportive therapy. No antiviral drugs are approved for treatment (Davis, Beckman and Tyler 2008).

Prevention of EEE involves vector repellant in humans and vaccination in horses (CDC 2010). Descriptive models of mosquito population density in urban and residential areas may be helpful in developing targeted strategies for vector control (Rochlin *et al*. 2008). Rochlin *et al*. (2008) found that many of the medically important vectors, including Cs. melanura, Ae. canadensis, and Cq. perturbans were more prevalent in rural areas compared to urban areas, while other species had higher percent compositions in urban areas, demonstrating the importance of understanding which species are competent vectors and the role they play in the disease transmission cycle. Recent announcements of snakes as an important source for the virus to overwinter may influence future EEE prevention strategies.

Cost analyses of insecticidal intervention to prevent EEE in eastern Massachusetts clearly indicate the economic advantages of preventing human disease (Villari *et al*. 1995). Insecticidal intervention costs were estimated to be between $0.7 and $1.4 million. In contrast, total costs per individual suffering severe residual sequelae from EEE were $2.5 million. Chronic illness was estimated to cost $0.4 million per year in the first three years post infection and then costs plateaued at approximately $0.1 million in subsequent years. By the time three study subjects reached 22 years of age, disease-related costs were $1.5 million, and had an additional estimated lifetime cost of $1.0 million for institutional care.

Lowest Consequence Zoonotic Priority Disease Pathogens

Diseases in this category are assessed to be of extremely low likelihood of occurrence, to be more controllable than other ZPDs, or to have limited or no information available about the likely economic impacts. These diseases include Nipah and Hendra virus, BSE, Ehrlichia ruminantium, Coxiella burnetii, and Akabane virus. However, as for midlevel diseases, if humans were to become affected, the impacts could be substantial.

Bovine Spongiform Encephalopathy

A study by Mathews, Bernstein, and Buzby (2008) revealed that costs from BSE-related market losses, slaughtering, disposal and selective culling in the UK (where over 95% of BSE cases occurred) exceeded $5 billion from the first case in 1986 until 2000. BSE influenced new rules and regulations in beef processing and rendering. It also substantially altered UK livestock trading patterns, which contributes substantially to the economic impact of diseases such as BSE. The potential for short term market fluctuations from a disease such as BSE is high.

A summary of BSE and vCJD as outlined by Mathews, Bernstein and Buzby (2008) allows a more complete understanding of why trade implications can cause such severe economic impacts. The first case of BSE was discovered in the UK in 1986. By 1990, live cattle exports from the UK were about 1/5 of what they were in 1988. This BSE UK outbreak didn't seem to have caused a long-term decline in the volume of EU beef exports, but the *value* of exports was reported to have decreased by some 37% and had not recovered by the time of the report, suggesting a downward shift in the demand of EU exported beef. A BSE episode in 1996 involving BSE cattle in the EU outside the UK and the possible link between BSE and vCJD were announced at approximately the same time. While the link between BSE and vCJD is uncertain, many scientists believe that vCJD results from ingesting the BSE prion, which is transmitted maternally or possibly through contaminated feed/food. Both diseases have apparently long incubation periods. Due to this possible connection, BSE moved beyond being solely an animal health issue to also becoming a food safety issue. At that time, the EU banned all UK beef exports, and most countries banned imports of beef and live cattle from the UK and several countries within the EU. UK exports to non-EU countries fell by 99% and UK exports of live cattle fell to zero. The long-term trend of beef consumption in the EU, resulting from eating habits and demographics, was already declining, but the outbreak impacted short run beef demand. The UK, and later the EU, implemented a ban on use of all cattle over 30 months of age for food and the EU imposed a destruction ban on such cattle. Also, a ban was implemented preventing use of all meat and bone meal in cattle feed. Prices for cattle and beef decreased implying a downward shift in demand. In 2000, more BSE cases were found outside the UK and vCJD cases in humans were identified in the EU outside the UK. EU beef exports dropped immediately 30-40% for November and December 2000, but there was quick recovery in the following months. The February 2001 FMD outbreak in the UK caused additional supply and demand shifts preventing further evaluation of the impact of BSE.

Cases of BSE in Canada and the U.S. have had substantial impacts on trade and prices of both cattle and beef for both countries (Mathews, Vandeveer and Gustafson 2006). New regulations following the BSE outbreak increased costs of beef production and processing, particularly for the rendering industry. The impacts chronicled by Mathews, Vandeveer and Gustafson (2006) of the first 8 cases of BSE in North America (5 cases in Canada and 3 cases in the U.S) are described here. Canada exported 47% of its beef production immediately prior to the first Canadian BSE case, which was announced on May 20, 2003. The U.S. immediately blocked imports of beef and live cattle from Canada, which caused an immediate 4% drop of beef supplies available to consumers in the U.S. Combined with a drought which caused U.S. cattle inventory reduction, the price of beef in the U.S. rose and peaked in October, 2003. Prior to the ban on beef/cattle imported from Canada, 60% of live cattle imports into the U.S. came from Canada. Thus, the initial consequence of BSE occurring in Canada was to improve the economic situation for U.S. cattle producers, but at a cost of increased prices to U.S. beef consumers. On December 23, 2003, the U.S. discovered its first case of BSE in a cow imported to the U.S. from Canada, causing U.S. beef exports to plummet, with 70 countries (including Japan, Korea, and Mexico, the three largest importers of U.S. beef) imposing import bans (Blayney Dyck and Harvey 2006). Prior to this, the U.S. had exported 9-10% of production output. In the weeks following the announcement, estimated cattle prices declined 4% for cows and 15% for choice steers. U.S. exports dropped from 2.5 billion pounds in 2003 to 461 million pounds in 2004, a decline of 80%. Strong domestic demand kept cattle prices in January 2004 above prices a year earlier despite the first announced U.S. BSE case, although prices were lower than they would have been had BSE not been identified in the U.S. Hog prices increased and poultry prices increased. Pork exports were 27% higher in 2004 than they had been in 2003, but this is partially explained by a weak dollar at the time that helped expand pork and poultry exports. The price for U.S. byproducts fell 20% by February, 2004 (from $10.40/cwt to $8.24/cwt). The authors conclude that the demand for beef in the U.S. did not shift because of BSE.

Consumer response to BSE varied considerably from country to country. U.S. consumer response was minimal, while European and Japanese response was more significant (Blayney *et al*. 2006). A study of U.S consumers by Kuchler and Tegene (2006) found that the variance in consumer purchases of beef is large with 75% of the variation explained by long term trends and seasonality. They concluded that deviations from purchase patterns following the discovery of BSE in the U.S. varied across beef products but were generally limited to short term impacts affecting prices no more than two weeks.

BSE caused increased costs for the beef packing industry (Coffey *et al.* 2005). The Food Safety and Inspection Service (FSIS) issued rules banning certain tissues (brains, eyes, spinal cord of cattle over 30 months) from human food, resulting in increased costs to these companies including training employees, altering existing Hazard Analysis Critical Control Point plans, changing capital investments, lowering revenues from loss of products which could no longer be sold, and prohibiting processing of non-ambulatory cattle. The net economic cost to the beef packing sector for these increased costs was estimated to be $200 million.

Hendra/Nipah Virus

It is believed that the horse is the only domestic species affected by Hendra virus and large fruit bats native to Australia are the only known reservoir of the virus (USAHA 2008). Nipah virus, which is similar to Hendra virus, was first recognized in pigs in 1999 during an outbreak that occurred in Malaysian pigs that also affected 258 humans with 100 human fatalities (Black *et al*. 2001). Nipah had emerged as a fatal disease in equine and human populations in Queensland, Australia in the mid-1990's (Murray, Seleck and Hooper 1995). Little is known or published about these diseases, but because of their zoonotic nature, there is concern about their potential as bioterrorism weapons. Outbreaks of these diseases anywhere in the world have the potential for major economic impacts, in large part because they are zoonotic pathogens, although the actual risks are unknown and presumably, natural occurrence of these diseases should have an extremely low probability (essentially zero) unless the virus becomes adapted to a species other than the large fruit bat and is maintained in an alternative species.

Coxiella burnetii (Q-Fever)

Coxiella burnetii is an intracellular bacterium that causes a disease in people known as Q-fever. Multiple hosts serve as reservoirs of infection including wild and domestic animals and ticks. Domestic ruminants are the most important source of infection for people, while ticks are the most important source for wild vertebrates (Ruiz-Fons *et al*. 2008). Pets can also be an important source of infection for people (Baud *et al*. 2009). Q-fever can cause a variety of clinical manifestations in people including hepatitis, endocarditis, anemia, miscarriage, fever, gastrointestinal symptoms including such as nausea, vomiting, and diarrhea, weight loss, atypical pneumonia, and death (Acha and Szyfres, 2003). Seroprevalence of this disease in people has been found to be high (4.6%), even in urban (London, England) populations with apparently rare exposure (Baud *et al*. 2009). The seroprevalence in a healthy population from northern Greece was estimated to be 7.5% (Pape *et al*. 2009). In Spain, the seroprevalence found in wild red deer, roe deer and cattle was estimated to be 29, 15, and 39 percent respectively (Ruiz-Fons *et al*. 2008). In northern Spain, where the disease is considered endemic, it was found that 68% of ewe flocks producing milk for human consumption had at least one ewe that was seropositive, and an estimated 8.9% of ewes tested were seropositive (Garcia-Perez *et al*. 2009).

Because Q-fever is vaccine-preventable and primarily affects people in high risk industries such as meat packing and agricultural production, Australia introduced the National Q-fever Management Program in 2000. Markov modeling was used to estimate the impact of Q-fever vaccination on the direct costs and outcomes of Q-fever over a 20-year period (Kermode *et al*. 2003). They found that increasing vaccination rates from 65% to 100% among meat industry workers resulted in an incremental cost per life year gained of \$20,002, and a cost per quality adjusted life years of \$6,294. The model predicted a decrease of 400 cases of Q-fever, a decrease of four deaths from Q-fever, and resulted in 43 discounted life years gained over a 20-year period at a cost of \$866,346. Increasing vaccine participation from 0% to 20% among agricultural industry workers resulted in an incremental cost per life year gained of \$24,950, and a cost per quality adjusted life years of \$7,984. Kermode *et al*. (2003) concluded that vaccination among high risk workers is cost effective and that there is economic value in public health strategies to encourage Q-fever vaccination among high-risk workers. Further evaluation of the Q-fever vaccination program found participation approached 100% among abattoir workers and was 43% for farmers (Gidding *et al*. 2009). Q-fever notifications (observations in the medical system) declined over 50% between 2002 and 2006. Conclusions from these studies suggest that vaccination programs should be considered in countries with high Q-fever disease burdens in their livestock populations.

IMPLICATIONS OF THE ECONOMIC IMPACTS OF FADs AND ZPDs AND WHY PREPAREDNESS IS A WICKED PROBLEM

Considerations for FADs Generally

Examining the epidemiology and economic impacts of FAD outbreaks generally helps inform understanding the types and degrees of complexities that may arise. There is a broad range of potential economic impacts of FADs (Umber, Miller and Hueston 2010), which makes planning for and handling any FAD outbreaks difficult. Economic impacts include disease mortality, depopulation of animals at risk for disease (preemptive depopulation), depopulation for animal welfare reasons, and associated productivity losses. Business interruption losses occur from forced downtime where repopulation of animals is prohibited by government. Economic impacts reverberate across the food chain to domestic consumers and foreign trading partners, and all of the involved industries between producers and consumers. Government costs may include indemnity payments, surveillance and vaccination, along with increased personnel costs. Indirect losses include economic impacts on tourism (e.g. ag tourism), veterinarians, feed companies and other related industries. Unemployment may increase in some industries and decrease in others. How any outbreak unfolds is unique, contributing to the variability of economic impacts.

How much to invest and what to procure for FAD preparedness and response is difficult to determine. Preparedness and response strategies based on expected mean economic impacts or previously reported economic impacts such as several references cited here could lead to decisions that would not be in the best economic interests of the parties being protected. This is in part because the numbers of FAD outbreaks that actually occur is not sufficiently large to adequately understand and represent all of the factors that should inform decision making regarding these outbreaks. Distributions of estimated impacts are often markedly skewed with a long tail for low probability high economic impacts. However, an actual outbreak, which may occur only once in several decades will be just one point on the distribution (Miller *et al*. 2012). The use of the average economic impact estimates and the typical disease epidemiology without the incorporation of variation and risks to guide preparedness and subsequent response will likely fail to provide the best guidance for decision making from either an epidemiologic or economic perspective.

The disease involved, the virulence and characteristics of the disease agent, the spread of disease, the species involved, the geographic origin of disease, and the density of the animals in and around outbreak areas, are among many other factors that all influence the manner in which an outbreak unfolds and this varies markedly between outbreaks. It is impossible to model all of the elements well that influence disease spread. Even the current national animal disease spread models run in supercomputing environments have many recognized deficiencies and limitations in modeling FAD outbreaks. Nonetheless, there is still value in using these models to study what may happen during an outbreak in advance, as best as possible, in order to gain a perspective on a variety of disease control and prevention options. Models might also indicate how different response strategies at various points in modeled outbreaks would influence disease spread and the economic consequences of the outbreak.

Many policy-makers' expectations are that models can provide more information than they can or should. Predictive models are desired. Models which are extremely flexible, that can answer real-time questions during outbreaks, and that do so quickly are desired. Many other model attributes are expected or desired that are either very difficult or costly to do or that cannot be done. These aspects all make dependence for decision making on models very problematic.

Also complex, and of high relevance is the ability to capture accurate data reflective of up-to-the-minute conditions (e.g. accurate situation reports) during an FAD outbreak. Lags occur of field information, and errors occur with samples, data and the associated interpretations. However, accurate knowledge of the outbreak is vital for the Veterinary Authority (USDA, APHIS, Veterinary Services in the U.S.) to make appropriate decisions in real time during an outbreak. The VA response to an FAD has an important influence on the economic impacts that will occur as a direct and indirect result of the FAD.

International trade policy and the behavior of trading partners have a significant influence on the economic impact of an FAD outbreak. International trade and trading partner response comes with its own difficulties for modeling. However, if not considered, any economic estimates will lack substantial accuracy for most U.S. animal industries, or any countries where animals or animal products are important exports. The OIE is recognized by the World Trade Organization and has a total of 178 Member Countries and Territories. The OIE sets the standards that govern international trade of animals and animal products. Member countries, including the U.S., agree to follow these guidelines and standards with regard to trade (OIE 2012), which outline member countries' responsibilities and appropriate responses when an FAD is recognized within its borders. These standards have generally been determined from the perspective of safety and health for animal populations, which is seen in the OIE Animal Terrestrial Health Code and the OIE publications on Diagnostic Tests and Vaccines. As an example, OIE recommendations for importation from FMD infected countries or zones for meat products states that the Veterinary Authority should require an international veterinary certificate that states that: 1) the consignment of meat comes from animals slaughtered in approved facilities subject to ante-mortem and post-mortem inspections for FMD; 2) the meat was processed to ensure the destruction of FMD virus in conformity with recommended procedures; and 3) necessary measures were taken to avoid contact with any potential source of FMD virus. Countries that have animals infected with FMD are limited to exporting canned, thoroughly cooked, or dried meats (Article 8.5.32), without regard to the status of the importing country. If the importing country had endemic FMD of the same type as the exporting country, these procedures wouldn't necessarily be of interest for the importing country, but they would add to the cost of product shipped from the exporting country. This example suggests that the economic consequences are not adequately considered even though the OIE impetus is guiding policy associated with trade of animals and animal products, an inherently economic relationship between countries.

The variation in trade for various production industries over time is another factor that increases the complexity and affects the accuracy of economic impact estimates. Specific changes in rules or regulations can be included as variables in an economic model, but the subtleties caused by changes in rules are likely inadequately captured and reflected in model output. The U.S. pork industry is illustrative of this point. From 1984 to 2009 the dollar value of U.S. pork exports grew from $250 million to approximately

$3.5 billion (Livestock Marketing Information Center). Pork imports remained relatively constant over this same period (Grimes, Plain and Meyer 2007). They suggest that this value of pork and pork by-products that can be attributed to exports grew from $1.97 per hog slaughtered in 1986 to $27.34 per head slaughtered in 2006. For the first six months of 2010, pork exports were 952K metric tons or 2.1 billion pounds, with a total export value of $2.35 Billion and an export value per head marketed of $44. The U.S. pork industry exported 24 percent of its total production (Pork Leader 2010). The US pork industry itself grew at an average rate of 0.8% per year over the last 21 years. While use of appropriate time series data and appropriately constructed, controlled and evaluated econometric models can estimate the economic impacts of an FAD outbreak, this estimation in the face of such profound industry changes remains a difficult task. The interpretation of results must be done judiciously, with a full understanding of the model's details.

Substantial complexities and a degree of uncertainty exist in any of the epidemiological models involved in making meaningful estimates of an FAD's impacts, spread and the associated prevention/control strategies. For instance, accurate and up-to-date data about locations and sizes of farms are not generally available in the U.S. and the National Agricultural Statistics Service data reflect county level information and counties can have substantial geographic size. Thus, since farm location within counties is not necessarily evenly or randomly distributed, parameterization of the underlying epidemiologic models is often based on assumptions which may not reflect the real distribution of farms over broad geographic areas and the structure of the involved industries. Limited information about the actual movement of animals from premises to premises is available. While estimates of the numbers of animals in transit are available, in reality, these movements are specific and nonrandom in nature. Non-randomness requires specific details about how movements actually occur, and this is not generally a part of the current epidemiologic models predicting disease spread.

Though not perfect, these epidemiological models are used as underpinning information (provide output) for input into national and international economic models, which in turn are complex, with a variety of assumptions and statistical approaches involved in making estimates. As one example, the output from epidemiological models may include a daily estimate of numbers of animals depopulated or dying from the disease. However, the data used for most economic models are most often quarterly or annual data. But the impacts on prices from an FAD shock often substantial daily changes. The impacts of such economic shocks are difficult to capture in a quarterly or annual economic model, which tend to smooth data or fail to obtain significant parameter estimates associated with variables placed in the model to capture the FAD shock effects. Assumptions must also be made about unknowns, such as consumer response, producer response, and response of all intervening parties in the food production chain.

There is a strong need for USDA policy which outlines the U.S. VA response during likely and specifically defined FAD outbreak scenarios. Without such policies in place, both government and industry preparedness is hampered. This preparedness should include parties' abilities to identify and target strategies which would limit economic impacts of FADs and promote business continuity. Industry's ability to prepare depends on a reasonable expectation of what the U.S. VA response would be to a range of potential scenarios for each of the FADs for which U.S. industry is at risk.

Wicked problems have many attributes including having complex interdependencies, where solving part of the problem reveals or creates other problems, or where there is incomplete, contradictory or changing aspects to the problem (Camillus 2008). These attributes combined with the social complexities and the many involved stakeholders with different values and priorities make a wicked problem difficult or impossible to solve.

All the above, taken together, makes it clear that preparedness and response for ZPDs are wicked problems. That is, the attributes of the models and problems, which include the variety of complexities, the range of potential outcomes, the large numbers of industries affected, the large numbers of involved individuals, companies and other stakeholders impacted, all suggest that determining likely economic impacts or appropriate preparedness and response strategies are at best extremely difficult and actually, most often, are wicked problems.

Considerations for ZPDs

ZPDs are sometimes FADs that also affect humans. The considerations above often also apply to ZPDs. Optimal preparedness and response strategies for

ZPDs are no easier to determine and also can be approached as wicked problems.

Additional complexities also must be considered for ZPDs. Narrod, Zinsstag, and Tiongco (2012) recognized the importance of assessing the economic impacts of zoonoses using a one health framework. The example applications they provide are mainly for endemic zoonotic pathogens, such as brucellosis and tuberculosis. The example they provide of HPAI was related to outbreaks in developing countries where the associated epidemiologic and economic models were simplistic in comparison to U.S. models. However, linking of animal and human disease transmission models has not generally been done in studies of ZPDs reported here. Nonetheless, it seems obvious that this lack of linkage can cause an incomplete understanding of the full spectrum of impacts of animal and human diseases, the associated stakeholders affected, the associated costs of diseases, and the benefits of control or disease responses. This lack of linkage also potentially distorts public choices away from socially optimal outcomes.

Use of disability adjusted life years (DALYs) allows for a quantification of the value of loss beyond the tracking of other costs (e.g. human medical and control costs). DALYs provide a weighted measure (death being given a weight of one, while impairments receive weights between zero and one) of the amount of human life years impacted by disease. DALYs reflect loss of life (years lost) and/or years lived with a disability. If dollar values are placed on DALYs (e.g. to be able to compare different investments that should be made in different areas within a particular country), these can vary across countries, further complicating ZPD considerations from a global perspective.

Economic consequences can be substantially higher for ZPDs compared to diseases that affect only animals if there are major direct consequences to human health during an outbreak. In a review paper, Velaso, Praditsitthikorn, Wichmann *et al*. (2012) found that predictions associated with the models for the economic evaluations of influenza pandemics had extremely large economic consequences with large variabilities (e.g. of incremental cost effectiveness for different types of interventions). These predictions were often based on assumptions which had a high degree of uncertainty and poor quality clinical data, especially for those studies conducted prior to 2009 (the time of the H1N1 pandemic). They also found considerable discrepancies for intervention regimes considered in the economic analyses, making study comparisons more difficult. Time horizons also varied considerably across studies.

Examining individual studies, it is not unusual to see output distributions that are often extremely wide. The means from the models are important but perhaps of equal importance are the variance, skewness, or higher moments reflective of the overall nature of the distributions that come out of these models. These moments have substantial impacts on the optimal economic decision making, especially where such outbreak events are relatively rare.

According to OIE guidance, if any major FAD (zoonotic or not) such as HPAI is diagnosed within the U.S., then all exports of the affected species and species at risk would immediately be shut off by the VA. There would be immediate notification of the OIE and trading partners, resulting in all major importing countries that are free of HPAI, and possibly some who are not, shutting off U.S. imports of at risk product and live animals. Thus, the implications for international trade are high. It is well recognized that the international trade of animals and animal products has increased over the last several decades. Countries such as the U.S., which are major exporters of animals and animal products, realize that international partners are important outlets for products. Blayney, Dyck, and Harvey (2006) suggest that the economic costs of trade disruptions from FADs can be explained by essentially three criteria: 1) the relative importance of meat exports in the affected country, 2) the relative importance of imports from a country affected by an FAD to consumers in an importing country, and 3) whether the FAD is zoonotic. Also, just as for FADs generally, prices can fall by 10-20% or more in a short period of time with ZPDs (Beach *et al*. 2008).

THE NEED FOR FURTHER ANALYSES AND DEVELOPMENT OF APPROPRIATE ZOONOTIC FAD POLICY AND RESPONSES

There is need for analyses that targets the economic implications of OIE guidance. Such analyses could be among the many considerations in changing OIE guidance. These analyses would need to reflect the economic impacts for a variety of trading partners. Most countries are OIE members and agree to follow their guidance and recommendations. Since OIE guidance generally gives greater weight to animal and human health considerations over economic implications, such analyses could prove very valuable for OIE member countries and could result in consideration of major changes in OIE rules and guidance for member countries. Analyses could also modify how guidance rules are implemented among member countries or modify bilateral or multilateral trade agreements.

There is a need for research investigating alternative responses other than those traditionally applied to fighting FADs, particularly in countries which have been free of particular FADs for a considerable period of time. Traditional approaches often include stamping out (which have involved depopulations of large numbers of animals). Traditional approaches also include (at least for a period of time) total stop movement orders preventing animal shipments for regions affected by the FAD and sometimes even across entire nations. Given the current approaches to US agricultural production, which have structured their industries to use just in time strategies for arrival of agricultural inputs (e.g. feed) and delivery of produced product (e.g. eggs and milk), movement of animals and products is required on an almost daily basis for many farms. Thus, stop movement orders are costly in today's structure of commercial animal agriculture, and can result in a large number of animals either depopulated for animal welfare reasons (e.g. animals continue to grow and farms run out of space because animals cannot be shipped to market) or alternately faced with consequences such as starvation and over-crowding. Stamping out, a common approach to fighting FADs, often prevents many animals from entering the food chain, even when they are not affected by the disease. This can potentially result in an enormous wastage of animal protein, the implications of which are becoming less politically and socially acceptable.

Additionally, with stamping out there is need for consideration of carcass disposal and the associated environmental impacts. Environmental impacts are often not adequately considered in estimating the costs from FAD outbreaks and associated response.

If animal production industries are structured in ways that optimize resource use, then the more that disease control strategies can allow as many animals to flow through normal channels as possible, the less deleterious will be the economic effects and wastage of protein. This will require a change in the way many FADs are approached; for example, more use of vaccinations in a vaccinate to slaughter (allow vaccination but require slaughter of all vaccinated animals within some specified time period) or vaccinate to live (allow vaccinated animals to live out whatever would be their normal life span, including use for breeding stock) approach during an outbreak would allow for more normal use and flow of the involved animals and animal products.

Identification of tipping/trigger points will be critical for implementation of a variety of control strategies that will be disease specific. For example, identifying the vaccination tipping points, or aspects of the situation report revealing epidemiological aspects of the disease as it unfolds that reveal when a disease cannot be eliminated easily by stamping out, is valuable use of epidemiological modeling. Similarly, there may be economic tipping points that need to be pursued and identified, such as an understanding of the number and descriptions of companies that would go out of business as a result of a particular control strategy.

Additionally, there is the need for on-going basic consumer education. Identification of best risk communication methods and messaging is needed in advance of an FAD outbreak. It is important for consumers to recognize that vaccination for FADs is no different in terms of the implications for the animal and/or animal products than other vaccinations routinely employed in food animal production. The entity delivering these messages must inspire confidence in the consuming public that animal products delivered to the consumer are safe and wholesome. Alliances between consumer serving industries such as restaurants and USDA may help develop more effective messaging for the US consumer and US trading partners.

There is a continuous need for further development of economic models based on improved epidemiological models in order to more accurately estimate various aspects of FAD outbreaks and to better predict the impact of various control strategies. Models should consider the short term severe shocks caused by production implications of the FAD, the consumer response to the FAD (both domestic consumer and international consumers of US produced meats), and also the VA response to the FAD. Additionally, continual updating of appropriate parameterization of these linked models must occur if they are to be of use. While easily stated, this work is complex, time consuming, and costly itself.

Development and implementation of new strategies are needed for control of FADs that allows for better business continuity. Compartmentalization, an approach which allows recognition of disease free premises or production systems based on biosecurity measures and surveillance, even in the face of an FAD outbreak, is one such strategy.

Economic models for ZPDs using a one health approach are currently not done routinely. There are only a few models which link well human and animal disease conditions and the associated economic impacts. These models are used most frequently for bacterial diseases where data and knowledge are more extensive, where diseases are more likely endemic and where control measures are more straightforward. In other words, even though such models may be fairly complex, they can provide simulations which are more likely to be realistic in comparison to simulations of ZPDs or FADs generally.

SUMMARY AND CONCLUSIONS

ZPDs can cause major economic losses and are disruptive to animal agriculture and human lives. There is an on-going need for the development of alternative approaches to responding to disease outbreaks; current approaches themselves may sometimes substantially and unnecessarily add to the costs of the disease or to the cost of response. If the focus of disease response is to minimize the long run economic impacts of an outbreak, the approach for disease containment, control and eventual eradication could be different than if the focus is to eliminate the disease as rapidly as possible. Different societal goals will require different types of economic analyses with appropriate objective functions and associated constraints to determine optimal solutions. Even with extensive and accurate disease spread and economic models, ZPD preparedness and response is a wicked problem.

There is a need for the USDA to conduct and publish publicly scenario analyses accompanied by established policies reflective of likely USDA response given particular scenarios. Indeed, conducting scenario analysis is recommended as a component of strategies for wicked problems (Camillus 2008). Published approaches will allow for more optimal preparations by State Departments of Agriculture, commercial production animal agriculture, related and supportive industries, and other animal agricultural stakeholders. Published approaches should also be shared with other countries. While country specific goals, objectives, industry structures, and constraints are different, still the feedback gained could improve response when outbreaks occur. Additionally, attitudes about and tolerance for government regulation vary country to country and may influence optimal economic choices for FAD response and control. Publishing likely or anticipated responses forces a recognition and consideration of all the complexities prior to an outbreak. Considerations pre-outbreak can be made with careful and more reasoned thought. Published approaches can be examined by others to check their accuracy and validity, and stakeholders can offer alternatives for consideration.

Similarly, agencies such as CDC and FDA, should publish scenario analyses for ZPDs with associated responses. These will allow for more optimal preparation by state and local public health agencies and departments and related NGOs, industries and interested stakeholders. With additional country to country comparisons, knowledge of country differences and the influence on country specific policy will help improve world control of ZPDs and FADs generally.

FOOTNOTES

Adjustments to reflect current US dollars were made using the Consumer Price Index tables located at: ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt in combination with historic values of currency exchange rates available at: http://www.x-rates.com

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ABBREVIATIONS

BSE = Bovine spongiform encephalopathy

CDC = Centers for Disease Control and Prevention

CSF = Classical swine fever

DALY = Disability Adjusted Life Year

EEE = Eastern equine encephalitis

END = Exotic Newcastle disease

FAD = foreign animal disease

FDA = Food and Drug Administration

FMD = Foot-and-mouth disease

HPAI = highly pathogenic avian influenza

JE = Japanese encephalitis

OIE = World Organization for Animal Health

VEE = Venezuelan equine encephalitis

USDA = United States Department of Agriculture

vCJD = variant Creutzfeld-Jacob Disease

VA = Veterinary authority

ZPD = Zoonotic Priority Disease

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