Human–Wildlife Interactions 10(1):91–102, Spring 2016

A benefit-cost analysis decision framework for mitigation of disease transmission at the wildlife–livestock interface

Stephanie A. Shwiff, USDA, APHIS, Wildlife Services' National Wildlife Research Center, 4101 LaPorte Avenue, Fort Collins, CO 80521, USA *Stephanie.A.Shwiff@aphis.usda.gov*
Steven J. Sweeney, Center for Epidemiology and Animal Health, USDA, APHIS, Veterinary Services, 2150 Centre Avenue, Fort Collins, CO 80526, USA
Julie L. Elser, USDA, APHIS, Wildlife Services' National Wildlife Research Center, 4101 LaPorte Avenue, Fort Collins, CO 80521, USA
Ryan S. Miller, Center for Epidemiology and Animal Health, USDA APHIS Veterinary Services, 2150 Centre Avenue, Fort Collins, CO 80526, USA
Matthew L. Farnsworth, Center for Epidemiology and Animal Health, USDA, APHIS, Veterinary Services, 2150 Centre Avenue, Fort Collins, CO 80526, USA
Pauline Nol, Wildlife–Livestock Disease Investigations Team, USDA, APHIS, Veterinary Services, 4101 LaPorte Avenue, Fort Collins, CO 80521, USA
Steven S. Shwiff, Texas A&M University–Commerce, 2200 Campbell Street, Commerce, TX 75428, USA
Aaron M. Anderson, USDA, APHIS, Wildlife Services' National Wildlife Research Center, 4101 LaPorte Avenue, Fort Collins, CO 80521, USA

Abstract: The economics of managing disease transmission at the wildlife–livestock interface have received heightened attention as agricultural and natural resource agencies struggle to tackle growing risks to animal health. In the fiscal landscape of increased scrutiny and shrinking budgets, resource managers seek to maximize the benefits and minimize the costs of disease mitigation efforts. To address this issue, a benefit-cost analysis decision framework was developed to help users make informed choices about whether and how to target disease management efforts in wildlife and livestock populations. Within the context of this framework, we examined the conclusions of a benefit-cost analysis conducted for vampire bat (*Desmodus rotundus*) rabies control in Mexico. The benefit-cost analysis decision framework provides a method that can be used to identify, assemble, and measure the components vital to the biological and economic efficiencies of animal disease mitigation efforts. The framework can be applied to commercially-raised and free-ranging species at various levels of management – from detailed intervention strategies to broad programmatic actions. The ability of benefit-cost analysis to illustrate the benefits of disease management projects per dollar spent allows for the determination of economic efficiency of alternative management actions. We believe this framework will be useful to the broader natural resource management community to maximize returns on financial and other resources invested in wildlife and livestock disease management programs.

Key words: benefit-cost analysis, disease management, economics, livestock, wildlife

A natural outcome of human population growth has been the juxtaposition of human activities and enterprises with natural features of the environment, including wildlife habitat. Expanding zones of contact between animal agriculture (e.g., livestock, captive wildlife, and companion animals) and free-ranging wildlife have arguably led to increasing risks to animal health, both for domestic livestock and for wildlife populations (Rhyan and Spraker 2010, Miller et al. 2013).

Disease transmission at the wildlife–livestock interface has the ability to significantly impact human health, threaten global trade and tourism, cause significant economic loss, and provide a potential mechanism for bio-terrorism. Evidence of these impacts can be seen through the examples of brucellosis, tuberculosis, avian influenza virus H5N1, foot-and-mouth disease (FMD), severe acute respiratory syndrome, human African trypanosomiasis, rabies, and anthrax.

Outbreaks of avian influenza virus H5N1 in Africa, Asia, and Europe resulted in an estimated loss to the poultry industry of $10 billion in 2005, as well as the destruction or loss of >200 million birds worldwide (FAO-OIE 2005, 2007). Epizootics of FMD in Taiwan and Great Britain illustrate the potentially devastating economic impacts of infectious disease transfer to livestock markets. In 1997, the number of FMD positive cases in Taiwan reached 1 million swine and >3.85 million animals were destroyed (Yang et al. 1998). The highly contagious nature of FMD led to an export ban on pork from Taiwan in March of 1997. Prior to the outbreak, the country exported >$1.6 billion annually, accounting for 15% of global pork exports. Over a decade after the outbreak, Taiwan had not regained its high level of exports and had much lower hog populations, while the United States, Canada, and Denmark increased their pork export market share as a result (Blayney et al. 2006). A 2001 outbreak of FMD in Great Britain resulted in estimated losses of £3.1 billion to the agriculture and food production sectors with additional tourism losses at least as great. It has been estimated that if FMD were to enter the United States, the economic losses would range from $12 billion to $228 billion with >30% of domestic livestock destroyed depending on the size and level of containment of the outbreak (Paarlberg et al. 2002, Boisvert et al. 2012, Oladosu et al. 2013).

In the United States, 79% of the livestock diseases that are reportable to the World Organisation for Animal Health have a wildlife component associated with their transmission, maintenance, or life cycle (Miller et al. 2013). The pathway to economic impact of disease transmission at the wildlife–livestock interface, hereafter referenced as "the interface," is usually from wildlife to livestock. But, the opposite case can become economically important when it helps maintain the disease reservoir in wildlife. A convergence of factors including land use changes, increasing frequency of contact between livestock and free-ranging wildlife, climate change, and the growth and intensification of livestock production have increased the need for a systematic process to understand the economics of controlling disease transmission at the interface (Jones et al. 2013). The monetary burden of disease transmission at the interface can be broadly divided into the impacts to livestock production, impacts to human and wildlife health, changes to consumption demand, and costs associated with disease management or mitigation.

The interfaces between wildlife, domestic animals, and humans provide many avenues to create economic losses resulting from disease transmission. Often, the most direct or immediate impact of wildlife disease transmission is the effect on livestock populations (Cleaveland et al. 2001, Tschopp et al. 2010, IFAH 2012, Narrod et al. 2012). Livestock morbidity and mortality cause direct losses within the livestock sector, and these losses in turn negatively impact economic sectors that are linked to livestock production. Additionally, consumer spending and tax revenue may be affected as prices and spending patterns change.

Human health impacts from zoonotic disease transmission can result from infectious contacts with wildlife or livestock, both of which may also exchange pathogens with one another prior to spillover into humans (Jones et al. 2013). Regardless of the pathway, the human health burden from zoonotic disease transmission has been well documented and includes death, illness, and disability (Cleaveland et al. 2001, Jones et al. 2013). Estimates of costs associated with these effects are available in the literature and can have broader economic implications as affected individuals, businesses, and governments reallocate resources to pay for treatment costs.

Consumers often react very quickly to real or perceived threats to human health and food safety and may avoid certain food products or tourist areas that are perceived as risky. These behaviors can be devastating to the economy. For example, in 2009, as pandemic H1N1 influenza spread into the United States, domestic pork consumption fell and exports from the United States decreased. Additionally, Russia and China, which represented almost 30% of the U.S. pork export market prior to the 2009 outbreak, banned the importation of certain types of pork products from the United States. As a result of reduced domestic pork consumption and declining pork prices, the U.S. pork industry lost an estimated $270 million in income in the second quarter of 2009 (Johnson 2009).

The main purpose of disease management at the interface is to reduce or eliminate the risk of disease transmission from wildlife to livestock. Success can be measured as the damage (i.e., losses, costs, etc.) avoided or in terms of the number of protected individuals, including humans, livestock, wildlife, and companion animals (Kapos et al. 2008). Management strategies are diverse and focus primarily on livestock populations (e.g., biosecurity measures, vaccination, husbandry practices). However, a few examples exist of disease management in wildlife populations. These include bovine tuberculosis (bTB, caused by *Mycobacterium bovis*), bovine brucellosis (caused by *Brucella abortus*), and rabies (caused by *Lyssavirus* spp.).

Individual producer estimates of the benefits and costs of management strategies are crucial to disease control efforts to gain producer involvement in mitigation efforts. Individual producer resources are limited, and investment in disease management will depend on the size of the operation, available resources, intended market of the finished product, education level of the producer, and production technology (Hennessy 2005, 2007; Beach et al. 2007). However, within any private market, producers will choose to invest in a particular management strategy up to the point where the expected private marginal benefits equal the expected private marginal costs (Beach et al. 2007). By their very nature, private markets provide neither an incentive nor a mechanism by which producers would consider the greater social costs or benefits of their disease management actions. As a result, one would expect private producers to under-invest in management from a social point of view (McCarthy et al. 2003). Because the broader society would prefer greater investment in disease management, this outcome is referred to as a "market failure."

Unlike individual producers, governments are expected to consider the total benefits and costs of disease transmission and mitigation. Disease management programs initiated by governments seek to achieve the optimal level of disease control by factoring in a broader set of components, including the impacts to overall disease containment in a region, impacts to wildlife and human health, and market impacts to consumers and the macroeconomy (Beach et al. 2007). Regardless of who initiates disease management at the interface, the economically efficient implementation of management efforts requires a comprehensive understanding of savings derived from a reduction in disease transmission.

In this paper, we provide a decision framework for benefit-cost analyses of disease transmission mitigation at the wildlife–livestock interface. Our methodology considers the potential impacts of disease mitigation to public health, animal health, and the economic sectors of a particular region. We illustrate the use of this framework by applying it to a previously conducted benefit-cost analysis, which evaluated a variety of disease transmission management options for a specific disease.

Methods

Development of a benefit-cost analysis decision framework for disease management

A general decision framework was developed for conducting benefit-cost analyses of management actions designed to reduce the risk of disease transmission at the wildlife–livestock interface (Figure 1). This framework is designed to measure and compare the value of management actions in terms of the direct benefits to impacted sectors (livestock, wildlife, humans, and their companion animals) and costs resulting from the management actions chosen to mitigate disease transmission in wildlife and livestock populations. When attempting to reduce disease transmission at the interface, wildlife and livestock managers are faced with a suite of management options. Livestock-focused management options include confinement of livestock or exclusion of wildlife through fencing or other means, improving biosecurity of farms, culling, livestock vaccination/treatment, and other husbandry practices (e.g., separation of sick animals) to manage disease. Wildlife-focused management options include population reduction, wildlife vaccination, and hazing of wildlife from livestock use areas. All disease management strategies have costs. The goal of these strategies is to reduce the probability of disease transmission at the interface, so the costs may be partially or completely offset by the value of reduced damage.

To measure economic efficiency, the framework allows for the quantitative

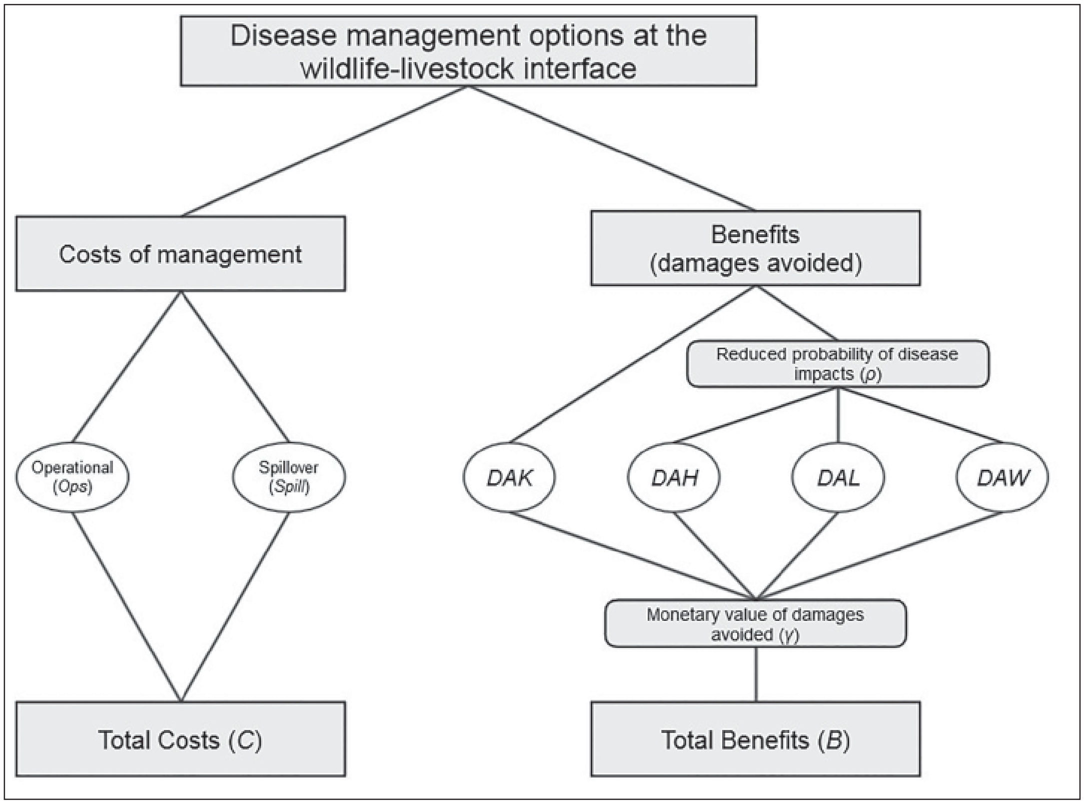

Figure 1. Decision-making framework for benefit-cost analysis of disease management options at the wildlife–livestock interface. Benefits (damages avoided) consist of consumption demand losses avoided (*DAK*), human health losses avoided (*DAH*), livestock losses avoided (*DAL*), and wildlife losses avoided (*DAW*).

or qualitative comparison of alternative management strategies resulting in reduced disease transmission between wildlife and livestock populations. Benefit-cost analysis is a commonly used tool to evaluate program activities by identifying and comparing the benefits and costs of alternative management efforts (Nas 1996). Another metric, cost-effectiveness analysis, may be used when benefits of alternate management programs are similar but difficult or impossible to monetize (Boardman et al. 1996). For example, cost-effectiveness analysis would be appropriate for a disease management project that captures the costs and number of animals saved associated with each management effort but is unable to make any animal valuation estimates. Economic efficiency is achieved through the management approach that produces the greatest net present value of the benefits (Cullen et al. 2001; Engeman et al. 2002, 2003; Cullen et al. 2005; Caudell et al. 2010; Laycock et al. 2011).

Determining management costs. Costs (C_{i}), driven by management actions ($i = 1, \ldots, n$), are often more straightforward to quantify than benefits (Shwiff et al. 2013*a*). The general category of management costs associated with wildlife disease transmission mitigation can be broken down into operational (*Ops*) and spillover (*Spill*) costs (Figure 1), represented by:

$$C_i = Ops_i + Spill_i$$

Operational costs represent the financial costs of project implementation and typically involve land purchase/lease, land management, equipment, labor, supplies, planning, negotiating, and other costs crucial to project completion and management. These costs can be obtained by keeping financial records of all aspects of expenditures related to the project for a post-project assessment of costs. Spillover costs are burdens external to a project and can include costs that arise from reduced agricultural production, lost recreational opportunities, loss of competing species or habitat, increased human conflicts, and other forgone uses of impacted wildlife species (Naidoo et al. 2006).

Assigning benefit values. Estimating the total benefits of preventing or reducing disease spread from wildlife to livestock requires quantification of market and non-market goods and services. An accepted methodology for determining these values is the damage avoided method, which uses the value of resources saved as a measure of benefits provided by the disease management program. In the current context, loss avoided is a function of 2 things: 1) impacts of a disease on livestock and/or wildlife in the absence of any management intervention, and 2) how effectively a particular management option in either wildlife or livestock reduces the probability (ρ) of disease impacts. Disease impacts may be estimated using stochastic simulation models or deterministic models, either in advance of an outbreak or after the outbreak occurs. Discussion of the factors that play a role in disease impacts are outside the scope of this manuscript, but include affected livestock and wildlife species, disease prevalence and susceptibility of host populations, contact rates between potential hosts, pathogen virulence and transmissibility, severity of clinical infection, presence of reservoir and carrier species, zoonotic potential, and the effectiveness of particular management options. The general framework presented in Figure 1 allows users to insert underlying equations and assumptions to parameterize the framework's variables.

Damage avoided (benefits) consist of 4 general components: consumption demand losses avoided (*DAK*), human health losses avoided (*DAH*), livestock losses avoided (*DAL*), and wildlife losses avoided (*DAW*), and their monetary valuations, γ. This relationship is represented by the following equation, where $i = 1, \ldots, n$ represents the management actions being evaluated.

$$\beta_i = \gamma_K (DAK_i) + \gamma_H (DAH_i) + \gamma_L (DAL_i) + \gamma_W (DAW_i)$$

For example, if 2 management options are being considered—1 in wildlife populations (e.g., vaccination) and 1 in livestock populations (e.g., fencing)—then $\beta_{W\,V}$ would represent the benefits derived from the 4 components (*DAK*, *DAH*, *DAL*, *DAW*) through vaccination of wildlife populations, while β_{LF} would measure the benefits derived from fencing around livestock facilities.

Damage avoided valuation (γ) is dependent upon the component being valued. Valuation of consumption demand losses avoided (γ_K) is a function of reduced consumption demand (domestic and international) for livestock products due to real or perceived threats to human health or food safety. This variable represents a reduction in quantity demanded (a shift in the demand curve) for the affected commodity and can be quantified by a change in consumer surplus with special care taken to avoid any possible double counting. The ability of individual consumers to substitute away from certain livestock products, as well as consumer taste and preferences, influence the size of this variable. Export bans, supply constraints, and movement restrictions can affect consumer ability to purchase the livestock product.

Valuation of human health loss avoided (γ_H) is a function of disease morbidity and mortality in humans and direct and indirect costs of disease management. We include companion animals in this variable. Therefore, if the disease is not zoonotic, this variable will reflect only companion animal costs. Direct costs include medical treatment expenses and reduced quantity and quality of human health (Jones et al. 2013). Many established methods exist to value direct losses to human health including quality-adjusted-life years (QALY), disability-adjusted-life years (DALY), or value-of-statistical life (VSL; Shwiff et al. 2013*b*). Both QALY and DALY measurements are expressly designed to estimate the impacts to human health as a result of disease burden. VSL provides a measure of the marginal value of a change in human mortality risk. Indirect costs include lost work time and companion animal impacts (Shwiff et al. 2007).

In terms of disease transfer at the interface, livestock losses are commonly reported as the most significant source of economic impact (IFAH 2012). Livestock mortality (γ_L) loss is based on the market value of the animal at time of death while morbidity loss can be calculated from the value of reduction in weight, decreased production, or increased veterinary costs.

Given that free-ranging wildlife typically do not have defined market values, valuation of wildlife (γ_W) can occur through survey methods, such as the contingent valuation method and travel cost method (TCM), as well as non-survey methods, such as benefit-transfer. The contingent valuation method is a survey-based, stated preference approach to estimate use and existence values associated with wildlife species (Kotchen and Reiling 1998). This method solicits responses from individuals regarding their willingness to pay for increased wildlife populations. By varying the amount that respondents are asked to pay, a social value of the outcome is constructed (Loomis 1990). TCM is another survey approach, which uses costs incurred for travel to quantify demand for recreational activities linked to a species of interest (Kotchen and Reiling 1998). TCM is based on the idea that as some environmental amenity changes, the amount that people are willing to pay to use it will change, and that the change in willingness to pay is revealed by a change in travel costs. The benefit-transfer method relies on benefit values derived from the contingent valuation method and TCM studies in 1 area, which can be transferred to similar species at another location while adjusting the values for differences in incomes or prices between locations.

Benefit-cost ratios. Combining the relevant information on benefits and costs allows the calculation of benefit-cost ratios (BCRs). Net benefits can be calculated by subtracting the denominator from the numerator.

$$BCR_i = \frac{B_i}{C_i} = \frac{\gamma_K(DAK_i) + \gamma_H(DAH_i) + \gamma_L(DAL_i) + \gamma_W(DAW_i)}{Ops_i + Spill_i}$$

BCR estimates of >1.0, or positive net benefits, indicate that the proposed management actions would be economically efficient.

Application of the framework to vampire bat rabies in Mexico

Vampire bat rabies causes significant impacts within its endemic range in Mexico. Animal testing costs, post-exposure prophylaxis costs, human mortality risk, and cattle losses comprise most of the economic costs associated with vampire bat-transmitted rabies in Mexico (Arambulo and Thakur 1992). Mitigation of the impacts can be achieved by 2 approaches: cattle vaccination and vampire bat population control. Anderson et al. (2012) conducted a benefit-cost analysis to evaluate these 2 mitigation strategies. We examined the methodology and conclusions of that analysis within the context of our framework.

Inclusion of specific benefits and costs depend on who is given standing, or whose perspective is being considered. In this case, private benefits and costs are those that accrue to livestock producers. A broader examination of the social benefits and costs considers not only impacts to producers, but also reductions in the use of human post-exposure prophylaxis and animal tests, which benefit individuals not necessarily involved in livestock production. To account for uncertainty in the true value of these parameters, Anderson et al. (2012) conducted Monte Carlo simulations, estimating a range of parameter values. These variables were applied to our benefit-cost analysis decision framework and are presented in Table 1, along with the analogous variables used in our framework. The benefit-cost analysis framework applied to this data is presented in Figure 2.

Three vampire bat rabies management scenarios are considered in this study. In the first, the producer is given standing so only the costs from cattle pre-exposure vaccination and the benefits derived from that vaccination are factored into the decision making process. Producer management costs are operational and consist of the total quantities of vaccine, coolers, ice, and fuel multiplied by their prices (Ops_L). Benefits are based on the cattle population (N) and the market price of cattle (γ_L) as well as the reduction in disease impacts (ρ_L), which is a function of rabies-related cattle mortality (M) and vaccine effectiveness (V).

The benefit-cost ratio (BCR) for the producer is determined by the following equation:

$$BCR_L = \frac{B_L}{C_L} = \frac{\gamma_L(DAL_L)}{Ops_L} = \frac{\gamma_L(\rho_L * N)}{Ops_L}$$

From a social perspective, there are 2 publicly funded strategies available to mitigate vampire bat rabies disease impacts. First, vampire bat populations can be reduced to decrease the likelihood of vampire bat contact with humans and animals, consequently reducing the number of post-exposure prophylaxis and animal tests. Second, public funding could be used to control vampire bat populations as well as subsidize cattle vaccination, which would reduce the number of post-exposure prophylaxis and

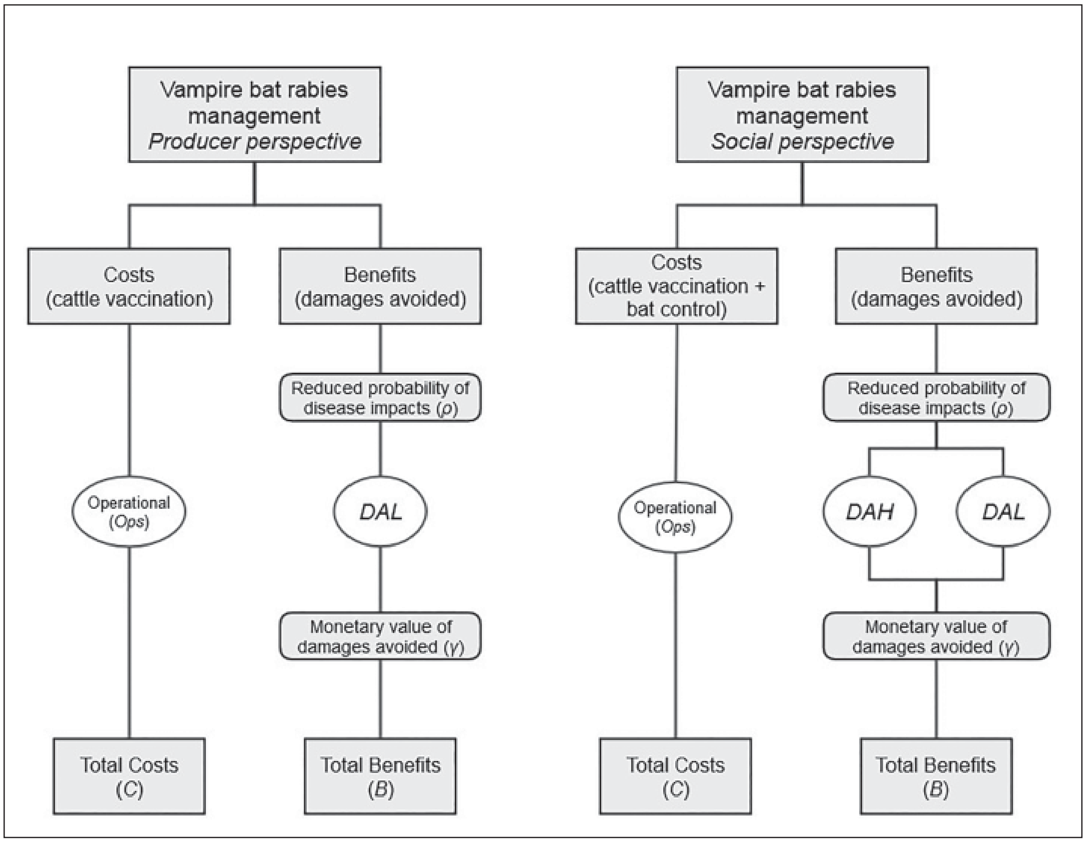

Figure 2. Benefit-cost analysis framework for vampire bat rabies management from producer and social perspectives. *DAH* indicates human health losses avoided; *DAL* indicates livestock losses avoided.

animal tests and would reduce cattle mortality. The first option is characterized by:

$$BCR_W = \frac{B_W}{C_W} = \frac{\gamma_H(DAH_W)}{Ops_W} = \frac{\gamma_{pep}(\rho_H * Q_{pep})}{Ops_W}$$

The second option combines management of livestock and wildlife populations and is characterized by the following equation. Because livestock vaccination is subsidized in this scenario, the social benefits of reduced animal tests are included.

$$BCR_{L,W} = \frac{B_{L,W}}{C_{L,W}} = \frac{\gamma_L(DAL_L)+\gamma_H(DAH_W)}{Ops_L+Ops_W} =$$

$$\frac{\gamma_L(\rho_L * N)+\gamma_{pep}(\rho_H * Q_{pep})+\gamma_{AT}(\rho_{AT} * Q_{AT})}{Ops_L+Ops_W}$$

Results

Anderson et al. (2012) calculated benefit-cost ratios for 3 alternative vampire bat rabies mitigation programs: a private option in which livestock producers bear the cost of rabies mitigation and reap the benefits, and 2 social options in which costs and benefits extend beyond producers to the broader society. The first social option involved vampire bat control, and the second option added subsidized cattle vaccination.

Under the private mitigation scenario, mean benefit-cost ratios ranged from 6.42 to 6.64 for the producer, indicating that for every $1 the producer spent to vaccinate cattle, >$6 in benefits were received. In other words, the return to producers in terms of reduced cattle mortality was >6 times the investment in vaccination. Clearly, from the producer's perspective, vaccinating cattle to reduce livestock mortality is economically efficient.

Benefit-cost ratios for the first social management option, bat population reduction, ranged from 0.36 to 0.38. This result indicated economic inefficiency in that for every $1 spent on the program, <$1 was returned in benefits. In contrast, including all the benefits and costs accrued by managing vampire bat rabies in both

Table 1. Variables used by Anderson et al. (2012) with analogous benefit-cost analysis framework variables.

Anderson et al. variables		Benefit-cost analysis framework variables	
Variable	Description	Variable	Description
N	Cattle population	N	Cattle population
M	Cattle mortality rate	ρ_L	Decrease of cattle disease impacts as a result of livestock vaccination
V	Vaccine effectiveness		
PEP	% PEP avoided	ρ_{PEP}	Decrease in disease impacts to humans as a result of bat control
AT	% AT avoided	ρ_{AT}	Decrease in disease impacts to humans as a result of vaccine subsidies
P_n	Market price of cattle	γ_L	Market price of cattle
P_{pep}	Unit cost of PEP	γ_{PEP}	Price of PEP
P_{at}	Unit cost of animal tests	γ_{AT}	Price of AT
Q_{pep}	Quantity of PEP	Q_{PEP}	Quantity of PEP
Q_{at}	Quantity of animal tests	Q_{AT}	Quantity of AT
P_v	Unit cost of vaccine	Ops_L	Livestock vaccination program cost
Q_v	Quantity of vaccine		
P_c	Unit cost of coolers		
Q_c	Quantity of coolers		
P_i	Unit cost of ice		
Q_i	Quantity of ice		
P_f	Unit cost of fuel		
Q_f	Quantity of fuel		
B	Bat control program cost	Ops_W	Bat control program cost

wildlife and livestock populations returned mean BCRs that ranged from 6.32 to 6.52.

Using our framework to map out the pathways by which benefits are derived and costs incurred allows for the straightforward understanding of variables involved in the determination of economic efficiency. When only operational costs and benefits to livestock and/or human health are considered, the results clearly indicate that the economically efficient management of vampire bat rabies consisted of intervention on the livestock side of the interface. This was the case whether rabies management is undertaken by producers or in the public sector. Intervention on the wildlife side of the interface is economically inefficient. Insight is gained through the framework in that results can be framed in the context of omitted components, and policy makers can determine the validity of the results given their valuation of the relative importance of the omitted variables. In this analysis, the impacts to consumer demand as well as the overall impact of rabies to vampire bat populations are likely to be negligible; therefore, even with the inclusion of information regarding these variables, the results are expected to remain valid.

Discussion

This manuscript provides a systematic framework to evaluate objectively the economic efficiency of methods to mitigate disease transmission at the wildlife–livestock interface. This method allows for comparisons of multiple management strategies across regions, diseases, types of livestock, and wildlife species. The utility of this framework is its flexibility; the general components that should be present in a benefit-cost or other economic analysis of disease management strategies are provided. Users can insert underlying equations and assumptions to inform the framework's variables. Modeling software can be used to simulate factors such as probability of disease transmission, estimates of morbidity and mortality losses for a particular disease, susceptibility of livestock populations, probability of pathogen transmission, likelihood of clinical infection, and others.

Conversely, the framework can be simplified in the absence of sophisticated parameter estimates. This approach can be used to provide more qualitative estimates of the components in the framework to obtain a less rigorous estimation of potential impacts and management costs. The level of rigor provided by the framework is a function of data availability. Additional flexibility in the framework allows it to be adapted to other settings, for example, to examine impacts at the wildlife–human interface or the wildlife–companion animal interface. This analysis focuses primarily on quantifying the impacts of disease transmission from wildlife to livestock; however, disease transmission from livestock to wildlife can also have costly implications.

Livestock production in the United States is interconnected and concentrated. Disease threats to food safety or livestock health have the potential to quickly ripple through a region, pushing impacts beyond livestock producers to the entire U.S. economy. Additionally, real or perceived risks to human health including direct contact with diseased animals as well as consumption of contaminated meat, dairy, or poultry products may result in broader economic impacts, some of which may be long lasting.

Management implications

Tighter budgets and increased fiscal scrutiny have resulted in limited resources to mitigate disease threats in the United States, emphasizing the need to use these resources efficiently by employing management strategies that will provide the biggest return on investment. The benefit-cost analysis framework described here can be used to identify, assemble, and measure the components critical to the economic efficiency of animal disease mitigation efforts. In many cases, a lack of data, or inability to quantify benefits, may drive economic analyses toward a simpler method, such as cost-effectiveness analysis. Given the importance and potential impacts of disease transmission at the wildlife–livestock interface, we created this methodology to aid in maximizing the return on resources invested in disease management programs.

Acknowledgments

The authors would like to thank Dr. Jack Rhyan from the WiLD-IT program and Dr. Kenneth Forsythe from the Center for Epidemiology and Animal Health for early reviews of this manuscript.

Literature cited

Anderson, A., S. Shwiff, K. Gebhardt, A. J. Ramírez, D. Kohler, and L. Lecuona. 2012. Economic evaluation of vampire bat (*Desmodus rotundus*) rabies prevention in Mexico. Transboundary and Emerging Diseases 61:140–146.

Arámbulo, P.V., III, and A. S. Thakur. 1992. Impact of zoonoses in tropical America. Annals of the New York Academy of Sciences 653:6–18.

Beach, R. H., C. Poulos, and S. K. Pattanayak. 2007. Farm economics of bird flu. Canadian Journal of Agricultural Economics 55:471–483.

Blayney, D. P., J. Dyck, and D. Harvey. 2006. Economic effects of animal diseases linked to trade dependency. Amber Waves 4:22–29.

Boardman, A. E., D. H. Greenberg, A. R. Vining, and D. L. Weimer. 1996. Cost-benefit analysis: concepts and practice. Prentice Hall, Upper Saddle River, New Jersey, USA.

Boisvert, R. N., D. Kay, and C. G. Turvey. 2012. Macroeconomic costs to large scale disruptions of food production: the case of foot-and-mouth disease in the United States. Economic Modelling 29:1921–1930.

Caudell, J. N., S. A. Shwiff, and M. T. Slater. 2010.

Using a cost-effectiveness model to determine the applicability of OvoControl G to manage nuisance Canada geese. Journal of Wildlife Management 74:843–848.

Cleaveland, S., M. Laurenson, and L. H. Taylor. 2001. Diseases of humans and their domestic mammals: pathogen characteristics, host range and the risk of emergence. Philosophical Transactions of the Royal Society B: Biological Sciences 356:991–999.

Cullen, R., G. A. Fairburn, and K. F. Hughey. 2001. Measuring the productivity of threatened-species programs. Ecological Economics 39:53–66.

Cullen, R., E. Moran, and K. F. Hughey. 2005. Measuring the success and cost effectiveness of New Zealand multiple-species projects to the conservation of threatened species. Ecological Economics 53:311–323.

Engeman, R. M., S. A. Shwiff, F. Cano, and B. Constantin. 2003. An economic assessment of the potential for predator management to benefit Puerto Rican parrots. Ecological Economics 46:283–292.

Engeman, R. M., S. A. Shwiff, B. Constantin, M. Stahl, and H. T. Smith. 2002. An economic analysis of predator removal approaches for protecting marine turtle nests at Hobe Sound National Wildlife Refuge. Ecological Economics 42:469–478.

FAO-OIE. 2005. A global strategy for the progressive control of highly pathogenic avian influenza (HPAI). Food and Agricultural Organization of the United Nations, Rome, Italy; and World Organisation for Animal Health, Paris, France.

FAO-OIE. 2007. The global strategy for prevention and control of H5N1 highly pathogenic avian influenza (HPAI). Food and Agricultural Organization of the United Nations, Rome, Italy; and World Organisation for Animal Health, Paris, France.

Hennessy, D. A. 2005. Biosecurity and infectious animal disease. CARD Working Paper 05-WP 413, Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa, USA.

Hennessy, D. A. 2007. Behavioral incentives, equilibrium endemic disease, and health management policy for farmed animals. American Journal of Agricultural Economics 89:698–711.

IFAH. 2012. The costs of animal disease. International Federation for Animal Health, white paper. Oxford Analytica, Oxford, United Kingdom.

Johnson, R. 2009. Potential farm sector effects of 2009 H1N1 “swine flu”: questions and answers. Congressional Research Service, Library of Congress, Washington, D.C., USA.

Jones, B. A., D. Grace, R. Kock, S. Alonso, J. Rushton, M. Y. Said, D. McKeever, F. Mutua, J. Young, J. McDermott, and D. U. Pfeiffer. 2013. Zoonosis emergence linked to agricultural intensification and environmental change. Proceedings of the National Academy of Sciences 110:8399–8404.

Kapos, V., A. Balmford, R. Aveling, P. Bubb, P. Carey, A. Entwistle, J. Hopkins, T. Mulliken, R. Safford, A. Stattersfield, M. Walpole, and A. Manica. 2008. Calibrating conservation: new tools for measuring success. Conservation Letters 1:155–164.

Kotchen, M. J., and S. D. Reiling. 1998. Estimating and questioning economic values for endangered species: an application and discussion. Endangered Species Update 15:77–83.

Laycock, H. F., D. Moran, J. C. Smart, D. G. Raffaelli, and P. C. White. 2011. Evaluating the effectiveness and efficiency of biodiversity conservation spending. Ecological Economics 70:1789–1796.

Loomis, J. B. 1990. Comparative reliability of the dichotomous choice and open-ended contingent valuation techniques. Journal of Environmental Economics and Management 18:78–85.

McCarthy, N., J. McDermott, and P. Coleman. 2003. Animal health and the role of communities: an example of trypanasomosis control options in Uganda. International Food Policy Research Institute, Washington, D.C., USA.

Miller, R. S., M. L. Farnsworth, and J. L. Malmberg. 2013. Diseases at the livestock–wildlife interface: status, challenges, and opportunities in the United States. Preventive Veterinary Medicine 110:119–132.

Naidoo, R., A. Balmford, P. J. Ferraro, S. Polasky, T. H. Ricketts, and M. Rouget. 2006. Integrating economic costs into conservation planning. Trends in Ecology and Evolution 21:681–687.

Narrod, C., J. Zinsstag, and M. Tiongco. 2012. A one health framework for estimating the economic costs of zoonotic diseases on society. EcoHealth 9:150–162.

Nas, T. F. 1996. Cost-benefit analysis: theory and application. Sage Publications, Thousand Oaks, California, USA.

Oladosu, G., A. Z. Rose, and B. Lee. 2013. Economic impacts of potential foot and mouth disease agroterrorism in the USA: a general equilibrium analysis. Journal of Bioterrorism and Biodefense S12:001.

Paarlberg, P. L., J. G. Lee, and A. H. Seitzinger. 2002. Potential revenue impact of an outbreak of foot-and-mouth disease in the United States. Journal of the American Veterinary Medical Association 220:988–992.

Rhyan, J. C., and T. R. Spraker. 2010. Emergence of diseases from wildlife reservoirs. Veterinary Pathology Online 47:34–39.

Shwiff, S. A., A. Anderson, R. Cullen, P. C. White, and S. S. Shwiff. 2013*a*. Assignment of measurable costs and benefits to wildlife conservation projects. Wildlife Research 40:134–141.

Shwiff, S., K. Hampson, and A. Anderson. 2013*b*. Potential economic benefits of eliminating canine rabies. Antiviral Research 98:352–356.

Shwiff, S. A., R. T. Sterner, M. T. Jay, S. Parikh, A. Bellomy, M. I. Meltzer, C. E. Rupprecht, and D. Slate. 2007. Direct and indirect costs of rabies exposure: a retrospective study in southern California (1998–2002). Journal of Wildlife Diseases 43:251–257.

Tschopp, R., S. Berg, K. Argaw, E. Gadisa, M. Habtamu, E. Schelling, D. Young, A. Aseffa, and J. Zinsstag. 2010. Bovine tuberculosis in Ethiopia wildlife. Journal of Wildlife Diseases 46:753–762.

Yang, P. C., R. M. Chu, W. B. Chung, and H. T. Sung. 1998. Epidemiological characteristics and financial costs of the 1997 foot-and-mouth disease epidemic in Taiwan. Veterinary Record 145:731–734.

STEPHANIE A. SHWIFF is a research economist and project leader at USDA, APHIS, Wildlife Services' National Wildlife Research Center. She received her Ph.D. from Colorado State University and has taught numerous courses in economics at Colorado State University and Colorado School of Mines. Her research interests include wildlife damage management economics, resource valuation techniques, and the economics of environmental management, with an emphasis on the use of benefit-cost analysis and econometrics. Her recreational activities include coaching youth soccer and mountain biking.

STEVEN J. SWEENEY has a professional background that encompasses 3 decades of research and management experience in wildlife ecology and animal health fields. Since 2006, he has been employed with the Center for Epidemiology and Animal Health as a wildlife veterinary medical offices and senior analyst working on wildlife/livestock health issues. Previously, he worked as a field team supervisor of wildlife brucellosis research with the USGS Northern Rocky Mountain Science Center and as a consulting wildlife veterinarian for Yellowstone National Park. Going back to his roots in the Pacific Northwest, he was a veterinary college instructor, terrestrial ecology program manager, and state wildlife research biologist. His favorite activities are watching and photographing wildlife, cartooning, exercising on the trail or at the gym, and spending time with family and friends.

JULIE L. ELSER received her B.S. degree in biotechnology from Montana State University and her M.A. degree in economics from Colorado State University. She is currently an economist at USDA, APHIS, Wildlife Services’ National Wildlife Research Center. Her research interests include the economics of rabies prevention efforts and wildlife damage management.

Ryan S. Miller is an ecologist, senior analyst, and project leader with USDA, APHIS, Center for Epidemiology and Animal Health. He has been addressing wildlife–livestock related issues for APHIS sinse 2002. He has been involved in multiple studies in basic and applied wildlife ecology, addressing a diversity of issues related to avian influenza, bovine tuberculosis, and brucellosis. He holds B.S. and M.S. degrees in forest management and ecology from Colorado State University and is currently completing a Ph.D. degree in zoology at the same institution. He is broadly interested in landscape ecology, with special interests in disease ecology and conservation biology, specifically in the mechanisms that drive contact and transmission of pathogens at the wildlife–livestock interface and how policy can be established to mitigate transmission at this interface. Specific study systems include the cervid–cattle interface, feral swine–livestock interface, and wild bird–domestic fowl interface.

Matthew L. Farnsworth is a senior scientist with Conservation Science Partners, Inc. His research includes using known habitat affinities and current distribution maps to estimate feral swine ecosystem invasibility, survival modeling incorporating landscape, environmental, and health variables for the Mojave desert tortoise, and landscape ecology focused on developing monitoring methods for species assemblages. He received a B.S. degree in biology from the University of California–Santa Cruz and an M.S. degree in wildlife biology and Ph.D. degree in ecology from Colorado State University.

Pauline Nol is a wildlife epidemiologist with USDA, APHIS, Veterinary Services, Wildlife–Livestock Disease Investigations Team in Fort Collins, Colorado. She works with her team members to develop science-based solutions to disease problems at the wildlife–livestock interface. Much of this research is focused on detection methods and vaccine strategies against brucellosis, bovine tuberculosis, and other diseases in various species of wild ungulates. She received a B.S. and D.V.M. degree from the University of Florida, an M.S. at the University of Wisconsin–Madison, and a Ph.D. at Colorado State University.

Steven S. Shwiff received his Ph.D. degree in economics from Texas A&M University in 1977. He is currently a professor of economics at Texas A&M University–Commerce. He is also Distinguished Professor of the China University of Geosciences–Beijing. His current research interests include modeling the damage to economies from both disease and invasive species using computable general equilibrium models. He has published >20 articles, numerous monographs, studies, and a book. He has been at Texas A&M–Commerce since 1990. He received his Certified Professional Forecaster designation in 2007.

Aaron M. Anderson received his Ph.D. from Colorado State University and currently works as an economist at the USDA National Wildlife Research Center in Fort Collins, Colorado. His current research interests include the economics of rabies prevention efforts, the performance of statistical models for discrete choice data, and the optimal control of wildlife responsible for crop damage or livestock predation.