Transboundary and Emerging Diseases

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ORIGINAL ARTICLE

Economic Evaluation of Vampire Bat (*Desmodus rotundus*) Rabies Prevention in Mexico

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Summary

Vampire bat rabies causes significant impacts within its endemic range in Mexico. These impacts include livestock mortality, animal testing costs, post-exposure prophylaxis costs, and human mortality risk. Mitigation of the impacts can be achieved by vaccinating livestock and controlling vampire bat populations. A benefit-cost analysis was performed to examine the economic efficiency of these methods of mitigation, and Monte Carlo simulations were used to examine the impact that uncertainty has on the analysis. We found that livestock vaccination is efficient, with benefits being over six times higher than costs. However, bat control is inefficient because benefits are very unlikely to exceed costs. It is concluded that when these mitigation methods are judged by the metric of economic efficiency, livestock vaccination is desirable but bat control is not.

Introduction

A conventional technique used to manage rabies in wildlife is oral rabies vaccination (ORV). Baits containing the vaccine are distributed into rabies endemic regions and inoculation occurs after the baits are consumed by the vector species (Sterner et al., 2009), and successful elimination of the domestic dog-coyote variant rabies from the United States was achieved in 2008 using this technique (Shwiff et al., 2008). Management of rabies in bat populations poses a management problem because vaccination of bat populations through ORV campaigns is not possible given current technology.

Rabies transmitted by the common vampire bat (*Desmodus rotundus*) is a major public health concern in subtropical and tropical areas of Latin America (World Health Organization, 2005). Infected vampire bats can transmit rabies to domestic mammals and humans through their haematophagous behaviour (Turner, 1975). In this region of the world, although transmission of rabies from bats to humans is more common than transmission by feral dogs (Schneider et al., 2005), vampire bats are the species most often responsible for the spread rabies to livestock (Acha and Málaga Alba, 1988; World Health Organization, 2005, 2007).

In Mexico, the common vampire bat is widely distributed and abundant in local concentrations (Lord et al., 1988). The expansion of villages and livestock range and the subsequent manufacturing of wells, buildings, tunnels and mines have opened areas as roosts that were previously unavailable, resulting in an increase in the transmission of rabies to livestock and humans (Flores-Crespo and Arellano-Sota, 1991). When rabies is transmitted to livestock or humans, in the absence of timely treatment, death occurs. The mortality risk to humans also leads to relatively high rates of post-exposure prophylaxis (PEP) use. Even when rabies is not transmitted, harm to livestock production from vampire bat feeding behaviour can be significant and includes damaged hides, weight loss and decreased milk production. All of these impacts have economic consequences for livestock producers, governments and local communities in the vampire bat rabies endemic region of Mexico (Acha and Málaga Alba, 1988).

Because eradication of rabies in bats is currently impossible, mitigation techniques to reduce damage caused by vampire bat transmitted rabies must be implemented. These techniques include pre-exposure vaccination of cattle and targeted management of vampire bat populations (World Health Organization, 2005). When administered correctly, pre-exposure vaccination significantly reduces rabies-caused cattle mortality. Vampire bat control management programs consist of field application of anticoagulants to the target species, resulting in multiple deaths because of colony grooming habits (Linhart, 1972). In Mexico, these techniques are currently implemented in a limited manner, with few cattle being vaccinated and bat control conducted only in select areas.

Numerous economic studies have characterized rabies-related impacts including the estimation of direct and indirect costs associated with wildlife rabies and benefit-cost analyses of ORV programs (Shwiff et al., 2007). In many of these studies, a major justification for the vaccination and/or animal control programs focused upon historic and estimated future frequencies and expenditures on PEP and animal rabies tests (AT). In Mexico, however, livestock losses comprise the majority of the economic costs associated with vampire bat transmitted rabies (Arámbulo and Thakur, 1992).

In this study, a benefit-cost analysis was conducted to evaluate the economic efficiency of a vampire bat rabies management program implemented in the entire vampire bat rabies endemic region in Mexico. The management program that was considered consisted of vampire bat population control and cattle pre-exposure vaccination. Economic efficiency was evaluated from both private and social perspectives, and Monte Carlo simulations were used to account for uncertainty inherent in the analysis.

Materials and Methods

A policy or action is judged economically efficient if the benefits produced outweigh the costs incurred, and inefficiency is implied when the value of resources used to produce some benefit outweigh that benefit. In this analysis, it is appropriate to judge efficiency from two standpoints: private and social. The proposed rabies management program consists of both a bat control component and a cattle vaccination component. If cattle producers incur the costs of vaccination, it is valuable to calculate the net benefit of these vaccinations where the benefit is reduced livestock mortality and the resulting increase in revenue. This allows efficiency to be judged from a private (the cattle producers') perspective. However, the vaccination program will also reduce the need for rabies testing, a benefit that does not accrue to the cattle producers. Additionally, the vaccination program may be subsidized. It is therefore desirable to also evaluate the program from a social standpoint, which accounts for all benefits and costs, regardless of their distribution. The bat control program is evaluated from a purely social perspective because the costs accrue to taxpayers while the benefits accrue to a combination of private individuals and the healthcare sector.

Efficiency can be measured in two ways: net benefits and benefit-cost ratios. While these may seem to provide equivalent information, there is a subtle difference. The net benefit and benefit-cost ratios calculated in this analysis assume the management program is fully implemented. In practice, it is possible that neither component of the management program is fully implemented. In such a case, the net benefit of the full program may not be directly applicable, but the benefit-cost ratios still provide useful information. Regardless of the scale of implementation, the benefit-cost ratios can be interpreted as the value of benefits provided by every Peso spent. This contrasts with the calculated net benefit, which is only applicable when the scale of actual implementation matches the scale of implementation for which the net benefit was calculated.

Calculation of the appropriate benefit-cost ratios and net benefits require estimates of each of the variables appearing in Table 1. While the full list of estimates for each of these appears in Table 3, an overview of how each was estimated is warranted given their importance in the analysis.

Twenty-four states in Mexico had cattle test positive for vampire bat rabies at least once between 1997 and 2006. These states, henceforth referred to as the rabies endemic region, were Campeche, Chiapas, Chihuahua, Colima, Durango, Guerrero, Hidalgo, Jalisco, Mexico, Michoacán, Morelos, Nayarit, Oaxaca, Puebla, Queretaro, Quintana Roo, San Luis Potosí, Sinaloa, Sonora, Tabasco, Tamaulipas, Veracruz, Yucatan and Zacatecas. Within the region these states make up, in 2003, there were 13.7 million susceptible cattle with a market value of approximately Mex$6840 each (SIAP, 2007).

Table 1. Variable definitions

Description	Variable	Description	Variable
Cattle population	N	Cattle price	P_n
Mortality rate	M	Vaccine effectiveness	V
Unit cost of vaccine	P_v	Unit cost of PEP	P_{pep}
Quantity of vaccine	Q_v	Quantity of PEP	Q_{pep}
Unit cost of coolers	P_c	Unit of cost of animal tests	P_{at}
Quantity of coolers	Q_c	Quantity of animal tests	Q_{at}
Unit cost of ice	P_i	Bat control program cost	B
Quantity of ice	Q_i	% of PEP avoided by bat control program	PEP
Unit cost of fuel	P_f	% of AT avoided by vaccine program	AT
Quantity of fuel	Q_f	Cattle price	P_n

Table 2. Benefit-cost ratios (BCR)

Livestock vaccination only (rancher)	$\mathrm{BCR}_{\text{vaccine, rancher}} = \dfrac{\frac{V}{100}\left[P_n\left(N\frac{M}{100}\right)\right]}{P_vQ_v + P_cQ_c + P_iQ_i + P_fQ_f}$
Livestock vaccination only (social)	$\mathrm{BCR}_{\text{vaccine, social}} = \dfrac{\frac{V}{100}\left[P_n\left(N\frac{M}{100}\right)\right] + \frac{\mathrm{AT}}{100}\left(P_{\mathrm{at}}Q_{\mathrm{at}}\right)}{P_vQ_v + P_cQ_c + P_iQ_i + P_fQ_f}$
Bat control only (social)	$\mathrm{BCR}_{\text{bat control, social}} = \dfrac{\frac{\mathrm{PEP}}{100}\left(P_{\mathrm{pep}}Q_{\mathrm{pep}}\right)}{B}$
Combined (social)	$\mathrm{BCR}_{\text{combined, social}} = \dfrac{\frac{V}{100}\left[P_n\left(N\frac{M}{100}\right)\right] + \frac{\mathrm{PEP}}{100}\left(P_{\mathrm{pep}}Q_{\mathrm{pep}}\right) + \frac{\mathrm{AT}}{100}\left(P_{\mathrm{at}}Q_{\mathrm{at}}\right)}{P_vQ_v + P_cQ_c + P_iQ_i + P_fQ_f + B}$

During the 10-year period between 1997 and 2006, 2769 cattle sent from the endemic region to a national laboratory tested positive for rabies (SAGARPA, 2007). Numerous studies have reported that this is a substantial underestimate of the actual number of cattle who contracted and subsequently died from vampire bat transmitted rabies (Prieto and Baer, 1972; Baer, 1991; World Health Organization, 2005). Conservatively, the official mortality rate as reported by the Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA) was more than double the mortality rate indicated by the number of animals that tested positive in a laboratory. Published estimates of cattle mortality owing to vampire bat rabies exposure estimated that between 90 000 and 100 000 head of cattle died each year in Mexico (approximately 1% mortality rate) (Acha, 1967). Additional reports related to specific study sites or recent epizootics estimated that the mortality rate ranges from 4% to >20% (Prieto and Baer, 1972; Baer, 1991; Martínez-Burnes et al., 1997). Given the wide range of published estimates for the purposes of this study, an estimate of 1% for cattle mortality will be used as a starting point.

Between 1997 and 2006, the average annual number of PEPs in Mexico was 955 at a cost of Mex$1500 per patient, and the number of AT were 283 at a cost of Mex$120 per test (SAGARPA, 2007). Owing to the uncertainty associated with the effectiveness of the rabies management programs, we estimated a plausible range of management program effectiveness where effectiveness is measured as percent reduction in cattle mortality owing to vaccination and percent reduction in PEPs and AT owing to bat control. These estimates are presented in Table 3.

Pre-exposure vaccination costs are the aggregated costs associated with vaccinating all cattle in the endemic region (rabies vaccine, syringe, cooler, ice and transportation costs). Estimates of these costs were based on observed prices in Mexico at the time the analysis was performed. The government-sponsored vampire bat control program cost was calculated on an annual basis and was based on the authors' knowledge of the costs' smaller-scale bat control efforts, which includes the salary of the capture teams and expenditures on nets, traps and other items. Individual costs associated with the cattle vaccination program and bat control program are presented in Table 3.

Table 2 displays the formulas used to calculate the four different benefit-cost ratios. For each, the equivalent net benefit is the numerator minus the denominator.

The calculation of the various benefit-cost ratios is based on twenty different variables. Because there is considerable uncertainty about the true value of these variables, two Monte Carlo simulations were performed to calculate the appropriate benefit-cost ratios. These simulations differed only in the degree of assumed uncertainty in the variables. The estimates of V, PEP and AT are in the form of a range, and it is assumed that these are uniformly distributed across that range. For the remaining variables, an expected value was estimated, but a range was not estimated. Given the inherent uncertainty in these estimates, each Monte Carlo simulation makes an arbitrary assumption about the distribution around each of these expected values. Specifically, it is assumed that these remaining variables follow a triangular distribution where the minimum and maximum values are ±25% (25% Monte Carlo) and ±50% (50% Monte Carlo) of the estimated expected value of that variable.[1] These alternative assumptions give an indication of how different degrees of uncertainty in the variables will affect the benefit-cost ratios. The specific assumptions made for each variable are given in Table 3.

[1]For symmetric triangular variables, the mode equals the expected value.

Table 3. Distribution and parameter assumptions

Variable	Distributions Uniform: U(lower, upper) Triangular: T(lower, mode, upper) 25% Monte Carlo	50% Monte Carlo
N	T(10 235 238, 13 646 984, 17 058 730)	T(6823492, 13,646,984, 20,470,476)
M	T(0.75, 1, 1.25)	T(0.5, 1, 1.5)
P_v	T(6.75, 9, 11.25)	T(4.5, 9, 13.5)
Q_v	T(10 235 238, 13 646 984, 17 058 730)	T(6 823 492, 13 646 984, 20 470 476)
P_c	T(45, 60, 75)	T(3420, 6840, 10 260)
Q_c	T(810, 1080, 1350)	T(540, 1080, 1620)
P_i	T(15, 20, 25)	T(10, 20, 30)
Q_i	T(4500, 6000, 7500)	T(3000, 6000, 9000)
P_f	T(6, 8, 10)	T(4, 8, 12)
Q_f	T(180 000, 240 000, 300 000)	T(120 000, 240 000, 360 000)
P_n	T(5130, 6840, 8550)	T(3420, 6840, 10 260)
V	U(75, 95)	U(75, 95)
P	T(1500)	T(750, 1500, 2250)
Q	T(716, 955, 1193)	T(477, 955, 1432)
P_{at}	T(90, 120, 150)	T(60, 120, 180)
Q_{at}	T(213, 283, 354)	T(142, 425, 283)
B	T(1 492 823, 1990 430, 2 488 038)	T(995 215, 1990 430, 2 985 645)
PEP	U(25, 75)	U(25, 75)
AT	U(75, 95)	U(75, 95)

Each simulation proceeded by randomly drawing values for each of the variables based on the assumed distribution and the parameter values of those distributions. The simulations were performed in Microsoft Excel and the *rand()* function was used to generate random numbers. This made the draws of the uniform variables simple, but draws from the triangular variables required an additional step. Random draws from a triangular distribution were simulated by generating a random number on the uniform interval [0,1] using *rand()* and evaluating the inverse of the triangular cumulative distribution function (Equation 1) at that number.

$$(1) F^{-1}(y) = \begin{cases} L + \sqrt{y(M-L)(U-L)} & \text{for } 0<y<(M-L)/(U-L) \\ U - \sqrt{(1-y)(U-M)(U-L)} & \text{for } (M-L)/(U-L)<y<1 \end{cases}$$

Given the drawn values of the 20 variables, the appropriate benefit-cost ratios and net benefits were then calculated. This process was repeated 200 000 times to sufficiently characterize the mean, median and variance or the benefit-cost ratios.

Results

The mean, median and variance of the 200 000 iterations in each simulation were calculated for the four different benefit-cost ratios. The social net benefit of the full vampire bat rabies management plan was also calculated (Table 4). For all of the benefit-cost ratios and the net benefit, the mean is larger than the median, implying that the distributions of these values are right-skewed. As expected, the variances of the results from the 50% Monte Carlo are significantly larger than those for the 25% Monte Carlo.

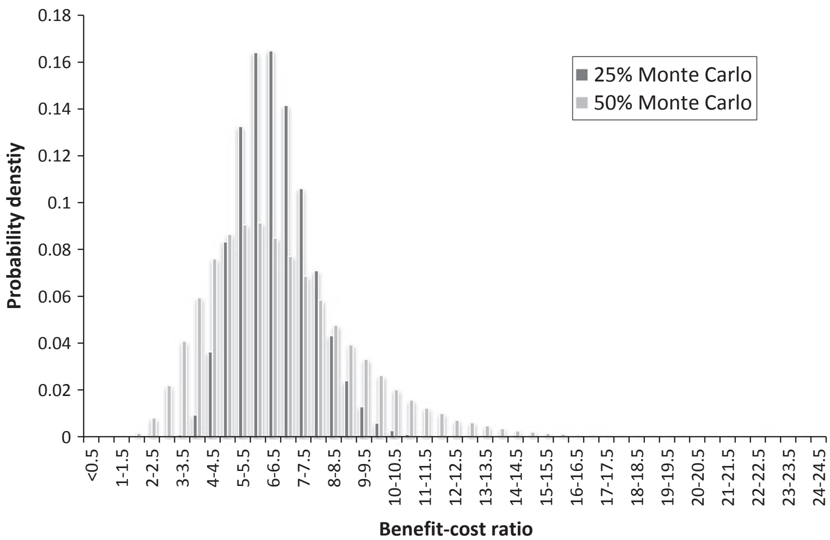
An approximation of the probability density function was also produced for the full program's social benefit-cost ratio (Graph 1), the vaccination component's social benefit-cost ratio (Graph 2), the vaccination component's private benefit-cost ratio (Graph 3) and the bat control component's social benefit-cost ratio (Graph 4). It can be seen that the distributions are right-skewed. The distribution from the 25% Monte Carlo have more mass around their means and medians, while the distributions from the 50% Monte Carlo have thicker tails, indicating a higher probability that the true benefit-cost ratio is relatively low or very high. Given the assumptions made about the variables in both the 25% and 50% Monte Carlo simulations, there is zero probability that the combined program's social benefit-cost ratio or the vaccination program's private and social benefit-cost ratios are less than one. However, under the assumptions of the 25% Monte Carlo, the probability that social benefit-cost ratio of the bat control program is greater than one is zero. Under the assumptions of the 50% Monte Carlo, the probability of that same outcome is only 0.7%.

Discussion

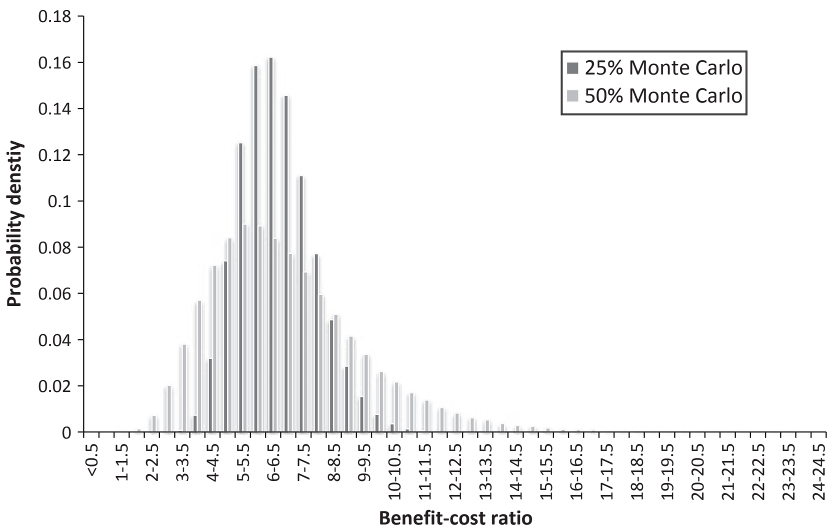
A comprehensive program to control the impacts of vampire bat rabies might include both a bat control component and a livestock vaccination program. However, the results from our analysis indicate that when judged purely by the metric of economic efficiency, the vaccination component is a better use of resources than the bat control program. The expected social benefit-cost ratio of the vaccination component is over six, indicated that for every peso spent on vaccinations, more than six pesos are realized in benefits. These benefits arise from both reduced cattle mortality and less need to test livestock for rabies. However, the private benefit-cost ratio of the vaccination program is only very slightly lower than the social ratio, implying the vast majority of

Table 4. Monte Carlo simulation results

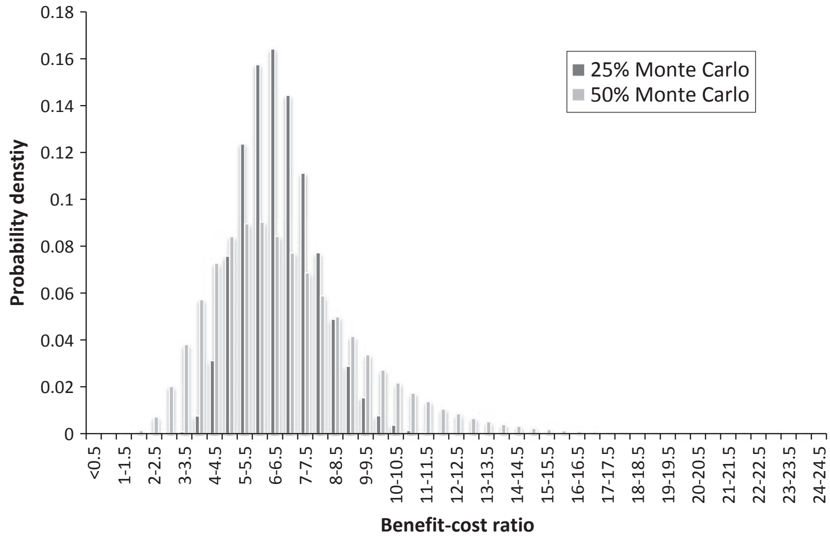
	Bat control program BCR	Vaccine program social BCR	Vaccine program rancher BCR	Combined social BCR	Combined social NB (Mex$)
25% Monte Carlo					
Mean	0.36	6.42	6.42	6.32	667 357 655
Median	0.35	6.31	6.31	6.22	656 284 026
Variance	0.02	1.50	1.50	1.44	2.11578E + 16
50% Monte Carlo					
Mean	0.38	6.64	6.64	6.52	667 787 752
Median	0.34	6.24	6.24	6.14	629 490 213
Variance	0.03	6.31	6.31	6.01	7.89226E + 16



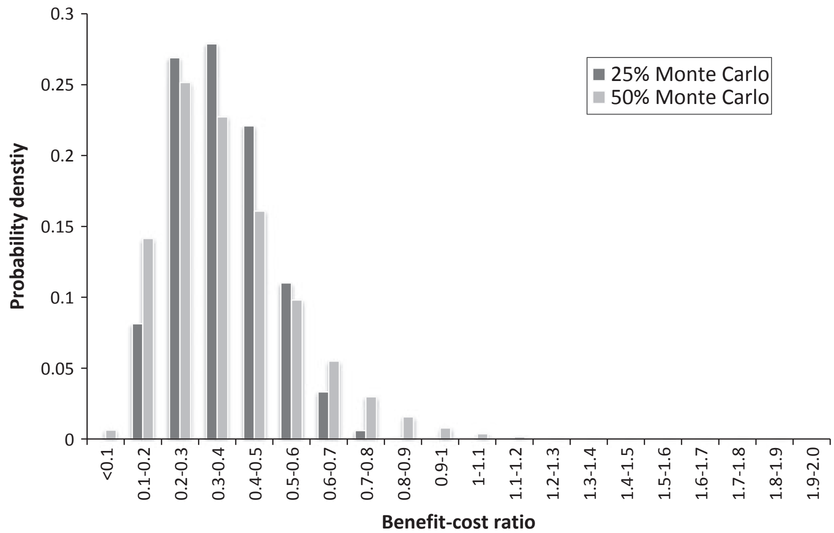
Graph 1. Probability density function of social benefit-cost ratios of combined programs.



Graph 2. Probability density function of social benefit-cost ratios of vaccination program.



Graph 3. Probability density function of private benefit-cost ratios of vaccination program.



Graph 4. Probability density function of social benefit-cost ratios of bat control program.

benefits provided by the vaccination program are realized by cattle producers. If subsidation of any vaccination program requires evidence of large social benefits beyond the benefits that accrue to cattle producers, it appears little subsidation could be justified, although the role of government assistance should not be completely discounted.

Given the large private benefits associated with cattle vaccination, it is curious that relatively few cattle are vaccinated. Several factors that may explain this include lack of education and awareness, as well as lack of access to the vaccine and veterinary care. It therefore seems clear that if the government is going to devote resources to a vaccination program, it can best do so in a way that increases producers' awareness of the problem, which shows the benefits of vaccination and eases access to the vaccine and veterinary care.

The results of the Monte Carlo simulation highlight the degree to which uncertainty in the data leads to uncertainty in the results. Given the assumptions of the two simulations performed in this analysis, the ranges of possible outcomes for all of the benefit-cost ratios are large. However, when considering any benefit-cost ratio, the value of one is the relevant threshold. Below this, costs outweigh benefits and the conclusion is inefficiency. Above one, the action is efficient. Our results indicate that the probability that the social or private benefit-cost ratios for the vaccination program are less than one is zero. It is thus reasonable to conclude that the vaccination component of the program is efficient. However, our results also indicate that the probability of the bat control component of the program producing a benefit-cost ratio greater than one is very small. Thus, this part of the program is likely inefficient. There is no need for these different components to be implemented together, and maximum efficiency is reached by implementing the vaccination component but not the bat control component.

While the two Monte Carlo simulations show how an assumed level of uncertainty leads to uncertainty in the results, the true value of any of the variables may lie outside the intervals assumed by even the 50% Monte Carlo. Assuming larger amounts of uncertainty in the variables will lead to a wider range of possible results. If enough uncertainty is assumed into the variables, virtually any result becomes possible. However, at some point further increases in the possible ranges the variables can take becomes implausible, and we believe the assumption we have made stop short of this point while still highlighting the potential range of results.

Vampire bat rabies causes significant impacts within its endemic region in Mexico. These impacts include livestock mortality, animal testing costs, post-exposure prophylaxis costs and human mortality risk. We evaluated the economic efficiency of two methods of mitigating these impacts: livestock vaccination and bat control. While economic efficiency is not the only way to judge the desirability of these methods, it is an important consideration. Inefficiency implies that the value of resources used by the method outweighs the benefits provided. If, in fact, mitigating the impacts of vampire bat rabies is economically efficient, such a finding deserves consideration by both livestock producers and policymakers within the affected region.

Our analysis indicates that a program of cattle vaccination is efficient, while a program of bat control is inefficient. Based on our assumptions, the probability that the costs of vaccination outweigh the benefits is zero. The expected benefits provided by vaccination are more than six times the costs, even when considering the costs of distributing the vaccines. Bat control, however, is highly unlikely to be efficient given our assumptions. This results from the high costs associated with the program, as well as the uncertain benefits it provides.

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