Bovine Brucellosis in the Greater Yellowstone Area: An Economic Diagnosis

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Introduction

Bovine brucellosis continues to frustrate livestock producers and wildlife managers in the Greater Yellowstone Area (GYA). The multifaceted nature of the issue makes it confusing and overwhelming. Economic principles, such as marginal analysis, externalities, imperfect information, incentives, and economic efficiency can bring clarity and focus to the situation. This paper uses economic principles to (1) identify the brucellosis issue's most important features, (2) diagnose their underlying causes, and (3) objectively discuss the following management questions: "What is the socially optimal level of brucellosis prevention?" "Are free markets capable of achieving this optimum?" "If not, what tools or policies will move us closer to it?" The purpose is to distill an overwhelmingly-complex issue down to its fundamental elements, and facilitate more objective discussion about potential solutions.

Background

1. Biology & epidemiology of brucellosis

Bovine brucellosis is a bacterial disease that causes abortions in domestic and wild ungulates. It is of concern because bison and elk in the GYA (the last known reservoir for the disease in the U.S.) occasionally transmit it to cattle, an event that triggers costly testing and movement restrictions. Susceptible animals contract brucellosis by ingesting objects contaminated with the causative organism (*Brucella abortus*), such as aborted fetuses, placental tissues and fluids, and forage (Meagher and Meyer 1994). Because brucellosis spreads primarily through abortions, testing and control policies focus primarily on sexually-intact cattle of reproductive age. Cow-calf operations are therefore more economically vulnerable to the disease than stocker or feedlot operations. Seventy percent of cow-calf producers in the West vaccinate some of their heifers against brucellosis (35% vaccinate all their heifers), but existing vaccines are only 65-75% effective (Cheville et al. 1996, Manthei 1959, USDA-APHIS-VS 2010).

2. Current brucellosis control policies

The few U.S. cases of bovine brucellosis that occur each decade are often detected in cull cows, sent to slaughter due to poor reproductive performance. A "test-positive" animal (i.e. an animal that has brucellosis antibodies, and *might* therefore be infected) triggers an epidemiologic investigation to identify the "index" herd (i.e. the animal's herd of origin) and all "contact" herds (i.e. herds that comingled or shared a fence line with the index herd). If brucellosis is successfully cultured from just one animal in the index herd, or if multiple animals in the herd test positive, the owner must decide whether to "depopulate" the entire herd, or attempt to "test-out" (Cook, personal communication); additionally, all contact herds are quarantined for testing.

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Testing-out requires the infected herd to be quarantined for at least one year, during which time they undergo multiple brucellosis tests. If additional test-positive animals are detected, those individuals are slaughtered and the testing-out procedure repeats. It can be expensive to meet a herd's forage requirements during quarantine, so producers typically choose to depopulate. Producers might also choose depopulation because testing-out causes the federal government to downgrade the state's brucellosis-free status from "Class Free" to "Class A" status, which triggers state-wide testing and movement restrictions. If a producer depopulates their herd, the state maintains its brucellosis-free status (as long as no other infected herds are detected within the following two years). The United States Department of Agriculture's Animal and Plant Health Inspection Service (USDA-APHIS) is currently reviewing its state-level disease classification system. They will likely replace it in the near future with a "disease surveillance area" approach. These two approaches and their relative efficiency are discussed in more detail later.

Producers in the GYA have adopted a variety of brucellosis management practices to reduce the risk of outbreaks in cattle and associated financial and emotional repercussions. Management practices include fencing haystacks, modifying winter-feeding practices, and calling state wildlife agencies to haze elk off private property, all of which discourage elk from commingling with cattle during high-risk months. Adult-booster vaccination, spaying heifers (because spayed or castrated animals cannot spread the disease and are therefore not test-eligible), and delayed grazing on high-risk allotments are also being adopted. Although it is difficult to quantify the extent to which these practices reduce risk, they certainly contribute to USDA-APHIS's goal of eradicating brucellosis.

3. Outcomes of current policies

USDA-APHIS began a brucellosis eradication campaign in 1934. At that time, 11.5% of adult cattle were test-positive for the disease (USDA-APHIS-VS 2009). After investing more than $3.5 billion in the campaign (Cheville et al. 1998), national herd prevalence is now less than 0.0001% (USDA-APHIS-VS 2009). In February 2008, for the first time in history, cattle in all U.S. states were simultaneously declared "brucellosis-free." This notable moment in history was short-lived. Montana lost its Class Free status in 2008 after two infected herds were detected within 24-months; it regained its status in July 2009. Idaho and Wyoming also lost Class Free status in recent years (Idaho from 2006 to 2007; Wyoming from 2004 to 2006). Wyoming detected another case in 2008, but retained its Class Free status because a second case was not detected within the following two years. As of October 2010, all states were again Class Free; however, test-positive animals had again been detected in a Wyoming herd.

4. Hurdles for brucellosis eradication

Tremendous progress has been made towards the eradication of brucellosis in U.S. cattle. One hurdle remains though: infected elk and bison in the GYA. Brucellosis was first observed in Yellowstone National Park's bison in 1917 (Mohler 1917). They are thought to have contracted it from cattle kept within the Park as a food source for employees (Meagher and Meyer 1994), and to have later spread it to the Park's elk. Elk outside the Park are thought to have contracted the disease directly from cattle (Meagher and Meyer 1994).

Today, approximately 50% of the Park's bison, and 64% of the Jackson bison herd, have antibodies to brucellosis (i.e. are "seropositive"); recall however that antibodies indicate previous exposure to the bacteria but not necessarily infection (Rhyan et al. 2009, Scurlock and Edwards

2010). The proportion of seropositive bison actually infected (i.e. culture positive) is highly uncertain, with estimates ranging from 7 to 46% (Cheville et al. 1998, Roffe et al. 1999). Approximately 3% of the Park's elk and non-feedground elk outside the Park are seropositive (Barber-Meyer et al. 2007, Ferrari and Garrott 2002). Seroprevalence among elk that use supplemental winter feedgrounds is much higher, ranging from 18 to 28% (Scurlock and Edwards 2010). As with bison, the proportion of elk actually infected is highly variable and uncertain. In past sampling efforts, 35 to 63% of elk that tested seropositive were actually infected (Scurlock 2010).

The potential for disease transmission between bison, elk and cattle makes the epidemiology of brucellosis highly complex. The significance of bison, elk and cattle in the economics and culture of the GYA makes the management of brucellosis highly contentious. Uncertainty about current levels of risk; disagreement over acceptable levels of risk; and imperfect information about alternative management strategies' effectiveness, expense and equity exacerbate the issue. Given the brucellosis issue's enormity, people tend to tackle it one small piece at a time. Although this makes the problem feel more manageable, it also makes it easier to lose sight of the brucellosis forest for its trees. Economic principles demonstrate how individual pieces of the brucellosis issue collectively create the forest, and how they can be managed to benefit it as a whole.

An Economic Diagnosis

1. How much brucellosis prevention is socially optimal?

Define "brucellosis control" as a variable input, and "prevention of brucellosis in cattle" as an output (the latter is really only an intermediate good that is ultimately an input to calf production). Economic theory says prevention of additional cases of brucellosis in cattle should proceed if the marginal benefit outweighs the marginal cost.

In a simplified world (one without animal disease regulations such as compulsory culling of infected herds, and movement restrictions during outbreaks), the marginal benefit of preventing a case of brucellosis consists primarily of increased the value of increased calf production. The marginal benefit of preventing a case of brucellosis should be constant regardless of the number of cases already prevented. After all, one less infected cow (regardless of the number of infections already prevented) implies one less aborted fetus and hence one more viable calf. If the calf market is perfectly competitive, the value of an additional calf will be the same no matter how many calves you sell. Together, these two arguments imply a constant marginal benefit to brucellosis prevention, i.e. a horizontal marginal benefit curve.

Marginal cost of brucellosis prevention is more complex. Suppose inputs to brucellosis prevention, such as vaccination and delayed grazing, exhibit diminishing marginal returns. Prevention of an additional case of brucellosis will, in this case, require more additional input than did the previous case. This implies each additional case is more expensive to prevent than previous cases, and hence the marginal cost curve is upward sloping. Heterogeneity in the circumstances leading to infection could also cause the marginal cost curve to be upward sloping. Cattle-to-cattle transmission in a feedlot, for example, would be cheaper to prevent than elk-to-cattle transmission on a remote grazing allotment. Arranging individual cases of infection by their cost of prevention would create an upward-sloping marginal cost curve.

The infectious nature of brucellosis, in contrast, creates a downward-sloping marginal cost curve, or at least applies downward pressure on marginal cost as the number of prevented cases increases. Because one infected cow can spread the disease to many others in the herd, prevention of one infected animal contributes to prevention in others. It becomes increasingly easy to prevent an additional case of infection the more cases already prevented (this is similar conceptually to increasing marginal returns, but stems from disease dynamics between animals rather than input characteristics). Conversely, it becomes increasingly difficult to prevent a susceptible cow from becoming infected as an increasing proportion of its herd becomes infected.[2]

The marginal cost curve's overall shape depends on the relative strength of diminishing marginal returns, heterogeneity, and infectiousness. Its shape and position, relative to the marginal benefit curve, have important implications for the desirable level of brucellosis prevention. Suppose the marginal cost curve decreases at first (due to infectiousness) and then increases (due to heterogeneity and diminishing marginal returns), eventually rising above the marginal benefit curve (figure 1a). Then the marginal cost of prevention will eventually outweigh marginal benefit, and the optimal number of prevented cases will be something less than eradication. This scenario represents standard assumptions and conclusions in economics. In reality, marginal cost could take a variety of forms and relative positions, although some are more likely than others. When paired with a horizontal marginal benefit curve (which again assumes each prevented case of brucellosis increases the value of calf production by the same amount), some forms and positions imply eradication is optimal, and others do not (see Peck 2010 for examples).

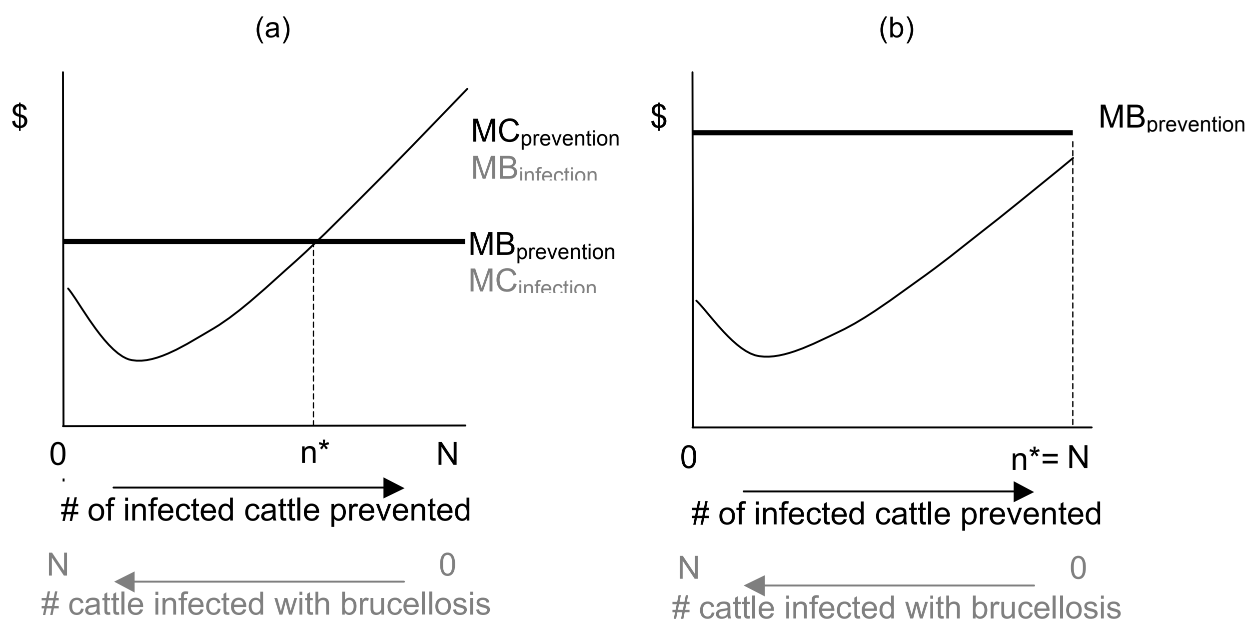
The exact shape and relative position of the marginal cost curve for brucellosis prevention is unknown. If we assume that diminishing marginal returns dominates infectiousness (i.e. the marginal cost curve is upward sloping) eradication would only be optimal if the marginal cost curve were located entirely below the marginal benefit curve (figure 1b). It is difficult to imagine increased calf production being sufficiently valuable to justify the resources necessary to prevent the last case of brucellosis, particularly if it arises from an elk-to-cattle transmission, which can be difficult to prevent. The point of this paper is not to determine the optimal number of cases to prevent, but rather to bring focus and objectivity to the eradication debate by framing it in terms of the marginal cost curve's most likely shape and position.

Those in favor of eradicating brucellosis sometimes take an alternative approach to answering the question "how much prevention is socially optimal?" They believe eradication is the best option because anything short of eradication imposes perpetual prevention and control costs that will eventually sum to infinity. This argument fails to consider two important points. First, even if brucellosis were eradicated in the U.S., we would still incur a perpetual cost to prevent its reintroduction (or incur a large up-front cost to help eradicate it globally). Second, it is incorrect to directly compare the total costs of eradication to the total costs of perpetual brucellosis management without first accounting for time preferences.

[2/] It may be tempting to capture infectiousness in the marginal benefit curve rather than the marginal cost curve. Marginal benefit is defined in this paper, however, as the additional benefit derived from preventing *one* additional case of brucellosis. Including infectiousness in the marginal benefit curve creates a situation in which the benefit of preventing one case is the prevention of *more* than one case. This is inconsistent with the definition of marginal benefit, or at the very least confusing. It is less confusing to capture infectiousness in the marginal cost curve instead.

Eradication will require relatively large upfront investments (e.g. in scientific labs and personnel to develop more effective vaccines). Perpetual brucellosis management, in contrast, will generate smaller annual costs, but they will be incurred every year into perpetuity (e.g. annual prevention and control costs punctuated by occasional large losses during outbreaks). Because people do not view costs incurred today equally to costs spread out over future years, the total cost (and benefits) of these two options cannot be directly compared without first accounting for time preferences. Even assuming a low social discount rate, e.g. 1 to 2%, perpetual management might be preferred over eradication, despite having a higher undiscounted total cost, because it pushes costs farther into the future (see Peck 2010 for a numerical example).

Figure 1. Marginal benefit (MB) and marginal cost (MC) of brucellosis prevention in an individual cattle herd containing N animals. The marginal cost curve' shape reflects increasing and then decreasing marginal returns to brucellosis prevention activities. Panel (a): MB is sufficiently low, or MC rises sufficiently fast, that MC eventually exceeds MB, so eradication is not optimal. Panel (b): MB is sufficiently high, or MC rises sufficiently slowly, that MB exceeds MC for each prevented case, so eradication is optimal.



2. Can markets achieve the social optimum?

If markets associated with brucellosis prevention worked perfectly, we would not need to anguish over the socially optimal number of cases to prevent (including whether eradication versus perpetual management is optimal), or how to prevent those cases as cheaply as possible. Individuals making decisions based on their private marginal benefits and costs would achieve the social optimum at least-cost. If free markets are imperfect, however, private decisions are unlikely to achieve the social optimum, and market interventions might be necessary. The market for brucellosis prevention suffers several imperfections, including incomplete markets, imperfect information, and externalities.

2.1 Incomplete Markets

Elk and bison play leading roles in the epidemiology of brucellosis in the GYA. Their abundance directly affects the probability of cattle becoming infected; population management is therefore an important and controversial element of the brucellosis debate. To identify the optimal elk, bison and cattle populations, we could construct a one-input, three-output social welfare maximization problem, in which the production possibilities curve captures biological and epidemiologic relationships between the species, and the isorevenue line captures their relative value. If free markets for these species were perfect, private management decisions would achieve the socially optimal combination of elk, bison and cattle.

Market prices unfortunately do not fully reflect society's value for these species because each species provides non-market goods and services (e.g. wildlife viewing, aesthetic appeal, cultural significance). When free markets are incomplete, stakeholders are unable to express, through mutually beneficial trades, all benefits they derive from elk, bison or cattle, or all costs they incur because of them. Suboptimal combinations of the three species are produced as a result.

2.2 Imperfect Information

Before producers can determine the optimal level of brucellosis prevention, they must first identify cost-minimizing combinations of management activities for achieving each prevention level. This requires information about the per-unit cost and technical effectiveness of alternative activities. Researchers at the University of Wyoming are currently estimating per-unit costs. Little is known, however, about the extent to which alternative management activities' reduce risk. Some management practices completely eliminate the risk, e.g. switching from cows to steers/spayed heifers. Most practices only partially reduce risk, however, and the extent to which they do so is highly uncertain and difficult to quantify. Imagine, for example, trying to quantify the extent to which fencing a haystack reduces the risk of elk-to-cattle transmission.

Producers face uncertainty not only about the extent to which various brucellosis management activities reduce risk, but also the underlying probability of their cattle contracting brucellosis prior to implementing preventive activities. They must therefore make brucellosis management decisions based on subjective beliefs about their underlying level of risk and alternative management activities' cost-effectiveness. This uncertainty makes it challenging for producers to identify cost-effective combinations of activities for alternative levels of prevention, and the privately optimal level of prevention.

Imperfect diagnostic tests are another source of uncertainty in the brucellosis issue. Infected cattle do not always immediately test positive following infection; animals that are actively incubating the bacteria can test negative (USDA-APHIS 2003). When a herd is known to be infected or exposed, imperfect diagnostic tests necessitate months of repeated testing to ensure all infected animals are detected. During this "testing-out" procedure, entire herds must be quarantined, including disease-free animals whose status cannot be immediately proven. Entire herds are therefore commonly culled to avoid quarantine costs. Quarantine and culling costs could be reduced significantly if brucellosis tests had greater sensitivity (the ability to detect all infected animals) and specificity (the ability to detect all uninfected animals) (Bercovich 1998).

2.3 Externalities in Cattle Production

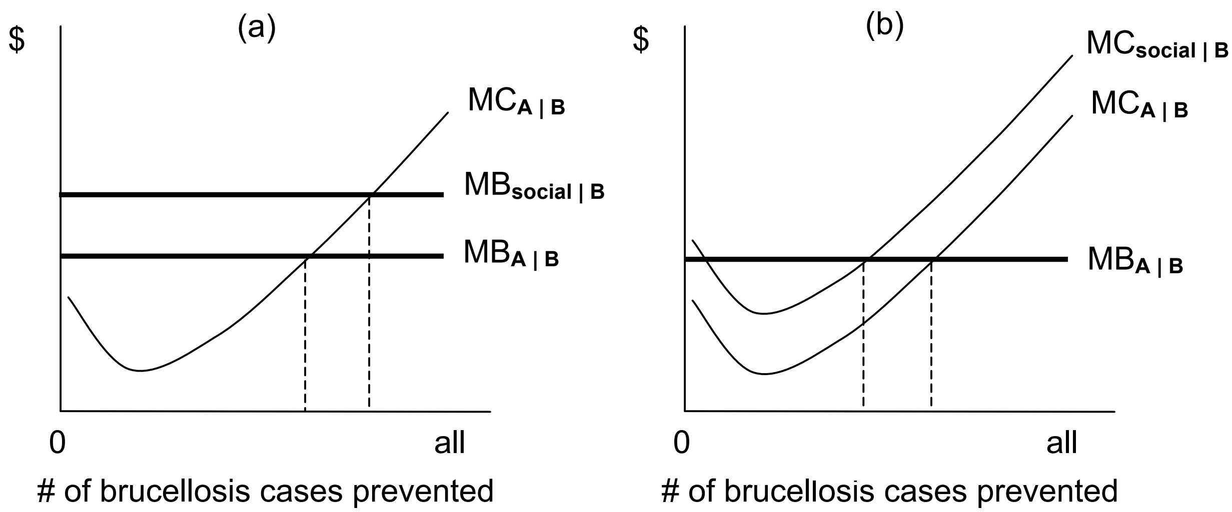
The infectious nature of brucellosis implies that an outbreak in one producer's herd generates costs not only for that producer (i.e. reduced calf production, and increased probability of other individuals in the herd becoming infected), but for neighboring producers as well. When a cow in one herd becomes infected with brucellosis, cattle in neighboring herds face a higher risk of contracting brucellosis, either directly from the infected cow itself, or indirectly from elk that contracted the disease from the infected cow (although the indirect route is theoretically possible, its empirical importance is thought to be quite limited).

Within-herd effects are reflected in the downward-sloping portion of the producer's private marginal cost curve (i.e. as more animals in the herd are prevented from becoming infected, it becomes easier to prevent the remaining cases). Cross-herd effects (i.e. as more animals in herd A are prevented from becoming infected, the cost of preventing cases in herd B changes) are captured instead as the difference between the social versus private marginal benefit (or cost) curve.

Suppose, for example, that producer A switches from a cow-calf to a stocker operation to reduce their brucellosis risk. This decision benefits producer B by eliminating the probability of their herd contracting brucellosis from herd A. Producer B can now achieve the same number of prevented cases with fewer resources (ignoring for now that their optimal prevention level might change, depending on how their total cost curve swings or shifts). Producer A's preventive activities, in this case, generate greater social benefit than private benefit (figure 2a). Producer A will therefore invest less in prevention than society would like them to.

Suppose instead that producer A fences haystacks to discourage elk from over-wintering on their property. This decision could potentially harm producer B by inadvertently causing more elk to over-winter on their property (particularly if their haystacks are unfenced). To achieve the same number of prevented cases, producer B must now invest more resources. The social cost of producer A's preventive activities, in this case, exceed private cost (figure 2b). Producer A will therefore invest more resources than is socially optimal, and prevent too many cases in herd A (and *cause* too many in herd B).

Figure 2. Private versus social marginal benefits and costs of producer A's brucellosis prevention activities (conditional on producer B's activities). Panel (a): producer A's activities positively affect producer B, so social marginal benefit exceeds producer A's private marginal benefit. Panel (b): producer A's activities negatively affect producer B, so social marginal cost exceeds producer A's private marginal cost.



The most direct means to correct a positive externality is to offer producers a subsidy for each prevented case of brucellosis. The subsidy would supplement the producer's marginal benefit from preventing a case of brucellosis. Ideally, it would supplement the producer's marginal benefit just enough to make it equal to society's marginal benefit. This would push the producer's level of prevention equal to the social optimum. Unfortunately, this policy cannot be implemented because the number of cases a producer prevents is unobservable. We observe the number of cases that occur in the presence of the activities, but can only speculate how many cases would have occurred in their absence. The opposite is true if a producer chooses not to adopt prevention activities.

An alternative means to increase the privately optimal level of prevention is to subsidize the cost of brucellosis management activities. This approach is easier to implement because we can more readily observe activity levels (e.g. the number of haystacks fenced). The marginal productivity of management activities would need to be known, however, to determine correct subsidy levels. Ideally, we would also only subsidize the most cost-effective activities, such that the socially optimal level of prevention is achieved as cheaply as possible. Again, uncertainty about the extent to which prevention activities reduce the risk of cattle contracting brucellosis would make it difficult to identify least-cost combinations.

2.4 Externalities in Wildlife Management

Externalities arise in another dimension of brucellosis: management of elk and bison that move relatively freely between public and private lands. If cattle were not present on the landscape, National Park Service (NPS) and state wildlife agencies would have little incentive to manage brucellosis in wildlife. Although the disease is exotic to North America (and some consider this adequate justification for control), it has not significantly impaired elk or bison populations, and is therefore not of great concern to wildlife managers. Furthermore, because some constituents disapprove of intensive brucellosis management activities, such as test-and-slaughter or vaccination, NPS and state wildlife agencies face a disincentive to take action.

Given cattle *are* present on the landscape, NPS and state wildlife agencies do have an incentive to manage brucellosis in wildlife. After all, for some portion of the year, elk and bison rely on habitat managed by private landowners (Coupal et al. 2004), many of whom own cattle. Reliance on private landowners for habitat provision therefore requires NPS and state wildlife agencies to engage in brucellosis management to help maintain goodwill. The Wyoming Game & Fish Department provides haystack fencing material and hazes elk from cattle feedlines. They also invested over $1 million in an elk test-and-slaughter program to reduce brucellosis seroprevalence in elk on supplemental winter feedgrounds. By maintaining good relationships with landowners, the agency ensures continued provision of elk habitat, and therefore larger elk populations (an important revenue source for the agency). Similarly, NPS has proposed a remote bison vaccination program within the Park (NPS 2010) in exchange for bison access to critical winter habitat north of Yellowstone National Park without compulsory brucellosis testing. The proposed vaccination program is currently under review (as required by the National Environmental Policy Act), and is expected to cost $9 million over a 30-year period if implemented (NPS 2010).

NPS and state wildlife agencies invest in brucellosis management presumably because it generates sufficient benefits for them to outweigh the costs. It is not clear whether their investment decisions consider benefits to cattle producers of preventing wildlife-to-cattle transmissions directly, or just the goodwill (i.e. wildlife habitat) generated when transmissions are prevented. If NPS and state wildlife agencies do not consider how their brucellosis management activities benefit cattle producers directly, they will invest too little in those activities relative to the socially optimal level, and too many wildlife-to-cattle transmissions will occur.

Incentives may be necessary to align the benefits and costs that NPS and state wildlife agencies derive from preventing brucellosis in elk and bison with society's. This could be accomplished by having society pay agencies for management actions that prevent wildlife-to-cattle transmission. Alternatively, society could require the agencies to pay some portion of losses generated when wildlife-to-cattle transmission occurs (a "polluter pays" approach). The second option is easier to implement, because outbreaks are easier to observe than prevented outbreaks (and it can be determined with some certainty whether elk or bison were the source). Regulatory approaches are a more politically popular means of correcting externalities. The court-mediated agreement between NPS, USDA-APHIS and the State of Montana requiring NPS to initiate a remote bison vaccination program serves as an example (NPS 2010). The agreement essentially forced NPS to internalize the costs brucellosis-infected bison impose on other stakeholders by legally requiring them to undertake management actions.

What tools or policies move us towards the optimum?

Now that we understand the market failures underlying the brucellosis debate, we can more objectively assess existing brucellosis policies and identify opportunities for improvement.

1. Incomplete markets

Incomplete markets are difficult to mitigate because they are often attributable to the underlying characteristics of the non-market good (which cannot be easily changed). It would be difficult, for example, to create a well-functioning market to capture people's existence value for bison. Nonetheless, we should continue to explore possibilities for new markets that (a) enable people to express their value for non-market goods, and (b) provide incentives for them to actually do so. In lieu of this, judicial venues (e.g. comment periods on proposed regulation) and collaborative forums (e.g. Wyoming's Brucellosis Coordination Team and the Interagency Bison Management Program) can help address incomplete markets by providing a means for people to express their non-market values.

2. Imperfect Information

Imperfect information about brucellosis may be one of the most difficult market failures to address. Little is known about the true prevalence of brucellosis in wildlife or the extent to which management activities reduce risk. Brucellosis tests and vaccines are also imperfect. As a result, (a) policymakers have only subjective notions of which prevention level is socially optimal; (b) their ability to identify least-cost management activities is limited, and (c) producers incurs additional costs because of prolonged quarantines and precautionary culling.

A few policies mitigate imperfect information, but more may be needed. USDA's current policy of quarantining and culling entire herds (not just test-positive individuals), for example, attempts to mitigate imperfect brucellosis tests by preventing undetected infected animals from transmitting brucellosis. This policy is accompanied, of course, by compensation to producer for culled herds (to increase their willingness to report suspected infections), but not for quarantine costs (which is the primary reason producers typically choose to depopulate infected herds rather than attempt to test out). Greater test sensitivity and specificity could dramatically reduce the cost of brucellosis control. Some state and federal dollars are dedicated to developing improving brucellosis tests and vaccines, but much more funding would be necessary for significant advancements to be made.

Research funds are also used to gather and analyze seroprevalence data for wildlife (e.g. Cross et al. 2010). Additional funds are needed, however, to determine the risk of cattle exposure to brucellosis at the livestock-wildlife interface, and the effectiveness of alternative management activities. This information would enable economists and epidemiologists to identify optimal management goals and the least-cost combination of prevention activities for achieving those goals. Many of the models needed to address such questions are already developed (e.g. Horan and Wolf 2005, Treanor et al. 2010, Xie and Horan 2009); however, they lack empirical parameter estimates necessary to prescribe specific policies. Care would be needed, however, to make sure the cost of data collection was less than the benefits it would generate.

3. Externalities

Current policies address externalities in the market for brucellosis prevention relatively well. Subsidies on brucellosis management activities (e.g. adult-booster vaccination) have narrowed the gap between private and social benefits of prevention. Collaborative processes have engaged state wildlife agencies and NPS, and raised awareness of the external costs of their inaction. This has pressured them to manage brucellosis in wildlife more actively (e.g.

vaccination and hazing). Additional policies to address externalities might be needed, but much has been accomplished already.

A few controversial policies that relate indirectly to externalities are currently being proposed. One such proposal is to close supplemental elk winter feedgrounds. People often assume closures would address externalities in the market for brucellosis prevention. More careful attention should be paid, however, when considering what market failures (if any) this would address. Elk winter feedgrounds were not created to address market failures in brucellosis prevention. They were created to prevent elk starvation and reduce depredation of private haystacks. Their creation addressed these problems, but generated unintended consequences (both negative and positive) for disease management. One negative consequence was higher rates of brucellosis in elk, and hence more infectious material in the environment for cattle to contact. One positive consequence was greater spatial separation of elk and cattle during the time of year in which abortions typically occur.

The potential effect of feedground closure on risk of transmission from elk to cattle is currently ambiguous. In the short-run, elk with relatively high rates of infection would likely migrate to private ranchlands in search of winter forage. Probability of transmission might increase as a result. In the long-run, more frequent elk-cattle interactions might become less problematic if infection rates in elk decrease due to lower population densities during high-risk months. Sportsmen and outfitters are concerned that native winter habitat is insufficient to support current elk populations and feedground closures might cause population decline.

The potential effects of feedground closure are sufficiently complex that a much broader analysis is required: one that examines market failures in the provision of elk and brucellosis prevention. Feedground closure would clearly affect brucellosis prevention, but many other effects would also need to be considered. While waiting for the feedground debate to be settled, Wyoming Game & Fish is exploring the potential for alternative feedground management activities (e.g. natural winter habitat improvement, a pilot elk test-and-slaughter project, low-density feeding, and shorter feeding seasons) to reduce the external costs of supplemental feeding. Cost-effectiveness is difficult to quantify for some activities (e.g. elk test-and-slaughter), which causes speculation and personal opinions, rather than objective comparison, to dominate management discussions.

Another controversial proposal is to replace USDA-APHIS's state-level brucellosis classification framework (i.e. if two or more infected herds are found in a two year period, the entire state loses its Class-A status) with a "disease surveillance area" framework, which would enforce testing and movement restrictions at the smaller "disease surveillance area" rather than the state level (USDA-APHIS-VS 2009). The World Organization for Animal Health already recognizes this "regionalization" approach, and uses it to minimize animal diseases' impacts on international trade.

USDA-APHIS is currently working with the states of Idaho, Montana and Wyoming to create a disease surveillance area in the GYA. Brucellosis outbreaks within the surveillance area would trigger the same epidemiologic investigations and farm-level control measures used currently. However, detection of multiple infected cattle herds within the surveillance area would not impose testing or movement restrictions on herds outside the area. To determine whether this disease surveillance area approach would address underlying failures in the market for brucellosis prevention, USDA's motivation for the original state-level classification system must first be understood. What market failures did policymakers design the system to address? Was it successful? How might the disease surveillance area approach improve upon it?

USDA's original motivation for a state-level brucellosis classification system is uncertain. One hypothesis is the federal government needed a way to increase state animal health officials' incentives to clean up infected herds (presumably to socially optimal levels). Intervention was justified because export of infected animals to other states imposes external costs by spreading the disease to previously uninfected areas. The state-level classification system punishes offending states by enforcing testing requirements (when two or more infected herds are detected within a two-year period), which makes moving animals across state boundaries more expensive. This forces offending states to internalize the costs they would otherwise impose on trade partners, and thereby increases their incentive to clean up infected herds.

Given the relatively high prevalence and widespread distribution of brucellosis in cattle when USDA-APHIS first initiated its eradication program, state-level enforcement probably seemed most appropriate and cost-effective, relative to regional or county-level enforcement. As the prevalence of brucellosis in U.S. cattle declined, and the disease became more geographically isolated, the system's ability to address externalities in a cost-effective manner diminished. Although it reduces externalities imposed on an offending state's trade partners, it achieves this by transferring external costs to producers within the infected state. Unfortunately, it transfers external costs to *all* producers in the state, not just those with infected herds, or those who knowingly put their cattle in risky situations. A portion of external costs previously imposed on "third-party" producers outside the state (i.e. those facing socially-acceptable levels of brucellosis risk) are simply transferred to third-party producers within the state.

The "disease surveillance area" approach improves on the state-classification system by transferring external costs to a smaller subset of producers, only those within the disease surveillance area, rather than in the entire state. A perfectly efficient surveillance area would include all producers whose herds face socially unacceptable levels of brucellosis risk (after accounting for risk-reducing management practices they adopt), but no third-party producers. Unfortunately, producers' brucellosis risks are uncertain, which prevents us from correctly identifying who belongs within versus outside the surveillance area. The surveillance area will therefore contain some producers whose cattle face socially acceptable levels of risk. Because these producers will be required to test animals before moving them across the surveillance area boundary, efficiency will be reduced. The disease surveillance area improves on the state classification system, however, by reducing the number of third-party producers subjected to brucellosis testing.

Although the surveillance area will include some third-party producers, they should not be worse off under the proposed approach than under the state classification system. Most producers in the proposed GYA disease surveillance area (or at least the Wyoming portion) sell cattle to buyers in other states, and are therefore already subject to brucellosis testing before test-eligible animals can be moved across state lines (if their state has lost Class-A status). Under the disease surveillance area approach, producers will simply have to test their cattle before moving them across the surveillance area boundary rather than the state boundary.

Producers in the GYA are rightfully concerned, however, that by eliminating state-level implications of brucellosis outbreak, political interest in the disease will wane and funding for research and management will disappear. From a social perspective though, investment in brucellosis should decrease if its consequences (i.e. potential gains from solving the problem) are somehow reduced (holding all else constant). Reduced funding of research and management causes the net welfare impacts of a disease surveillance area to be ambiguous for producers within it. Producers outside the surveillance area, however, will clearly be better off because they will no longer have to test cattle before moving them across state lines.

Conclusions

This article attempts to bring renewed clarity to the brucellosis debate by abstracting away from the issue's overwhelming details and focusing instead on its root causes. Economic principles, such as marginal analysis, discounting, missing markets, imperfect information, and externalities provide an objective means to diagnose the issue's root causes. This in turn enables us to better understand the fundamental nature of the conflict and identify more productive steps forward.

Economic principles indicate, first and foremost, that the control of brucellosis is not an end, but a means for improving society's well-being. Additional effort to control brucellosis should only be made if the additional benefit outweighs the additional cost. Economic principles also imply that because people tend to discount future benefits and costs, perpetual management might be preferred over eradication even if it is more expensive in the end.

Missing markets and externalities explain why private individuals, state wildlife agencies, and the National Park Service tend to invest too little in brucellosis prevention, relative to the social optimum. They clarify why government interventions and incentives might be justified (assuming their administrative costs do not exceed their benefits), and whether existing and proposed policies actually address underlying sources of market failure or simply transfer the costs of failure to a different subset of stakeholders.

Lastly, imperfect information makes it difficult to quantify all pieces of the economic puzzle necessary to identify the socially optimal quantities of elk, bison and cattle, the socially optimal level of brucellosis prevention, or the least-cost combination of activities to achieve it. Nonetheless, economic principles provide an intuitively-appealing framework that should enable stakeholders to engage in more objective discussions of the issue, and eventually identify an effective solution.

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