Applying an ecosystem approach to brucellosis control: can an old conflict between wildlife and agriculture be successfully managed?

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Brucellosis is a hotly debated topic in the western United States. For decades, this disease has pitted conservationists against ranchers, as well as against federal and state government agencies, particularly in Montana and Wyoming. Bison and elk are the primary wildlife disease reservoirs, and cattle the primary species of agricultural concern. Here, we briefly summarize the disease's etiology and ecology in wildlife and discuss recent developments in the sociopolitical landscape and in scientific research that could result in improved management. Applying some key principles of ecosystem management is crucial to improving brucellosis control in wildlife.

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Brucellosis in bison (*Bison bison*), elk (*Cervus elaphus*), and cattle is caused by *Brucella abortus*, a bacterium introduced to the US via European livestock. *B abortus* was first detected in bison in Yellowstone National Park (YNP) in 1917 (Cheville *et al*. 1998), and in elk as early as 1930. In wildlife and cattle, uninfected animals contract the disease primarily by licking birth exudates of infected herd members; however, bacteria localize in a variety of organs and can often be cultured from lymph nodes and mammary glands of infected animals on postmortem. Grazing on contaminated forage is a less likely intraspecies transmission route. Human brucellosis (known as undulant fever or Bang's disease) is usually caused by consuming unpasteurized dairy products and/or handling infected animals. *Brucella* bacteria are well-adapted to, and have coevolved with, ungulates and rarely cause severe morbidity or mortality in these hosts. However, in humans the disease is painful, debilitating, and chronic. Prior to an intensive state–federal brucellosis eradication campaign initiated in 1934, infection was common among the general public as well as in slaughterhouse workers and veterinarians. Now, undulant fever rarely occurs in the US, although it remains a problem in countries with less reliable pasteurization systems (Young 1995). When the disease does appear in the US, it is usually caused by *Brucella melitensis*, a species that does not occur in bison or elk, and is traceable to consumption of unpasteurized dairy products from sheep and goats (Chomel *et al*. 1994). Cattle producers must vaccinate and test for brucellosis (at frequencies depending on the brucellosis classification of the state in which they are operating), and if a positive animal is identified, usually the entire herd is slaughtered.

In a nutshell:

- Current management of brucellosis in wildlife is not based on principles of disease ecology
- Brucellosis will only be successfully controlled when solutions are conceived and implemented on ecosystem scales appropriate to wildlife, rather than implemented on local scales or adapted from agricultural management plans
- If interactions between humans, wildlife, and agricultural species can be successfully managed to control brucellosis, the resulting strategies could serve as a model for developing sustainable policies to negotiate other multi-host infectious diseases (eg chronic wasting disease)

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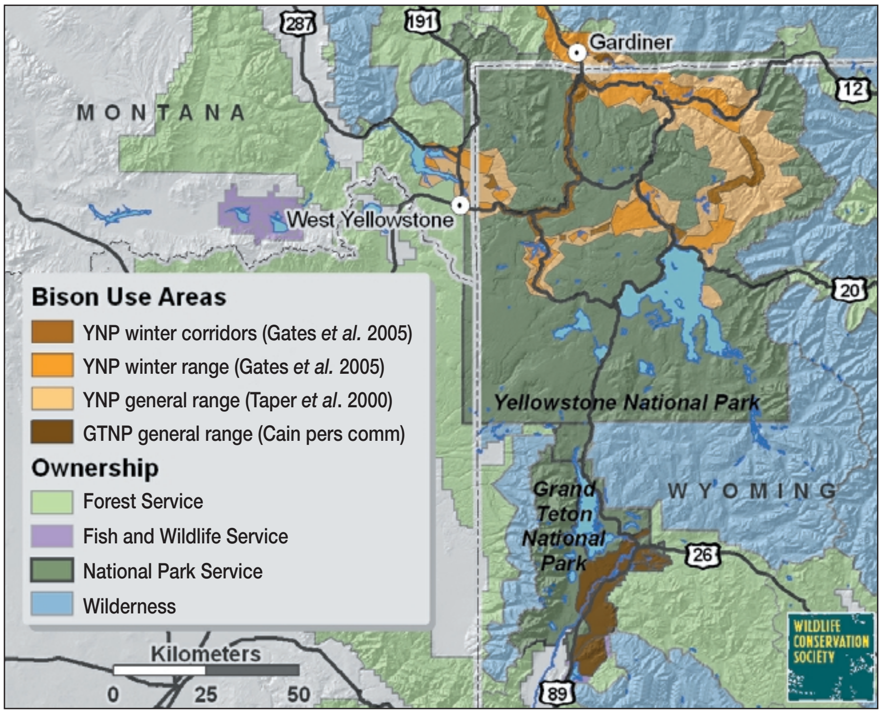
The current standoff

Major disagreements exist between conservationists and ranchers about the degree to which elk and bison, the two main wildlife reservoirs of brucellosis in the western US, should be controlled and managed in order to minimize the risk of disease transmission to cattle. Many ranchers, as well as the federal agencies responsible for brucellosis management, have operated under the assumption that as long as wildlife pose any risk of transmitting disease to cattle, wildlife species should bear the brunt of control measures. Conversely, conservationists have argued that (1) because brucellosis causes little measurable morbidity and mortality in wildlife species, these species should not be culled on public lands for the financial convenience of the cattle industry, and (2) that in order to minimize the risk of disease transmission, ranchers and federal and state agencies should be responsible



Courtesy of A Taivola

Figure 1. *Bison use areas in the GYE; bison in the GYE average 45–50% seropositivity for brucellosis. Datasets from Gates* et al. *(2005) and Taper* et al. *(2000) were digitized from hardcopy and are meant to generally represent winter bison ranges (Gates* et al. *2005) and varied use bison ranges (Taper* et al. *2000) within YNP. The data from Cain were obtained in shapefile format and represent the annual bison range within and near Grand Teton National Park.*

for limiting the presence of cattle (particularly females) on public lands. Transmission of brucellosis to cows, rather than bulls or steer, is the most serious concern for ranchers, because the usual manifestation of brucellosis in cattle is abortion of calves. To date, brucellosis control in wildlife has been managed erratically; bison are subject to the highest level of disease control measures, such as being slaughtered when they attempt to leave the confines of YNP, whereas elk are allowed to roam and migrate with relatively few restrictions. There have been no known cases of brucellosis transmitted from bison to cattle, but in Wyoming and Idaho multiple elk-to-cattle transmissions have been detected through DNA testing. The bacterial strain responsible for one of Wyoming's recent outbreaks was 99% genetically identical to *Brucella* cultured from elk wintering on the Muddy Creek feed ground (Galey 2005). As it is likely that elk will continue to be implicated in brucellosis outbreaks, their freedom relative to bison may be limited in the future. Here, we will look at the divergent approaches to brucellosis control and the problems to which such inconsistency has given rise.

The formulation of existing brucellosis control policies has taken decades, involved numerous lawsuits, and been fraught with hostility between rival interests. Virtually since brucellosis was first discovered in bison, various attempts have been made to control the disease in this species. Nevertheless, although there are isolated herds scattered throughout North America that have been "cleaned" of brucellosis, attempts to eradicate the disease in bison have failed (Figure 1). In the Greater Yellowstone Ecosystem (GYE), millions of dollars have been spent in pursuit of this elusive, and many conservationists would say misguided, goal.

■ Why do things differently now?

In the past 3–5 years, Idaho and Wyoming's cattle industries each suffered several brucellosis outbreaks; both states lost their federal designation as brucellosis "Class Free" and were demoted to "Class A". As a result, regional and national agricultural policy makers and wildlife managers have been forced to admit that current policies have not succeeded in keeping western cattle brucellosis-free. Thus, now is an ideal time for discussion and alteration of brucellosis control strategies. If a productive discussion of this issue could be accomplished, it would be taking place at a crucial moment in the history of conflicts between conservationists and agriculture and ranching in the American west. The economy of the west has changed such that state agency managers, federal managers, and politicians cannot automatically assume that the public will agree that agricultural interests must always come first. Wildlife tourism, including visits to National Parks, now contribute hugely and visibly to the economies of western states. In addition, recent events (outlined below) have added to the importance of producing a timely and critical examination of methods and policies for controlling brucellosis on an ecosystem-wide scale. As such, this paper is intended not just as a critique of current management policies, but also to spur positive change in entrenched and contentious disease management policies. A logical and rational discussion of some of the central, unresolved issues may help to forge compromises and solutions that are based on sound science and that make sense in terms of ecosystem preservation. Our hope is that new solutions, in the face of evidence that present management strategies are failing, do not simply take the form of harsher versions of fundamentally flawed strategies, as seems to have been the historical pattern.

■ A confluence of recent events

First, Montana, Wyoming, and Idaho now recognize that interstate cooperation will be necessary to control brucellosis on an ecosystem scale, and that unconnected state efforts are insufficient. Second, scientists have gathered a critical mass of data about effective measures to control brucellosis in wildlife. Vaccination and test-and-slaughter programs have been in place long enough so that their ability to control disease under different circumstances can be assessed, particularly in conjunction with advances in disease modeling. If this available data can be used as the basis for policy formulation, more successful, cost-effective, and sustainable disease control methods will result. For example, researchers at the US Geological Survey have collected 5 years of data on the persistence and survival of *B abortus* in the environment. Studies evaluating parameters such as how long aborted fetuses harboring brucellosis bacteria remain in the environment before they are scavenged, and how long the bacteria survive on grass and dirt (Clark *et al.* 2005), are vital for assessing the risk of brucellosis transmission from bison to cattle through shared forage, a major point of contention in formulating policies. Current policies regulating bison movements outside of YNP are expensive, divisive, and so far not justified by existing data. For example, despite the lack of evidence that bison transmit brucellosis to cattle, draconian policies preventing bison from leaving the park have been in force in certain areas (Figure 2a). By June of 2006, the federal Animal and Plant Health Inspection Service (APHIS) and Montana's Department of Livestock had culled more than 1000 bison (nearly a quarter of YNP's bison herd). State wildlife agencies and the National Park Service are under pressure from federal agricultural agencies to quickly (by 2007) devise individual herd plans to eliminate brucellosis in wildlife.

Our purpose here is to: (1) suggest ways to modify and implement brucellosis control policies so that they are more in line with the precepts of ecosystem management; (2) discuss research, particularly in the realm of wildlife disease modeling, that can be used to formulate more effective and sustainable management policies; and (3) identify long-term research priorities and goals for brucellosis control in wildlife. In order to simplify the process we have divided the paper into discussions of various principles of ecosystem management, accompanied by a set of short-, medium-, and long-term objectives (Tables 1–4).

We hope to illustrate how controlling brucellosis in wildlife through policies based on ecosystem management, and on sound principles of disease ecology, could pave the way for addressing a variety of wildlife–agriculture conflicts. For example, many environmentalists feel that the same lack of an ecosystem approach that has plagued brucellosis control also occurs in chronic wasting disease (CWD) management. CWD could have dire consequences for wildlife due to the disease's high fatality rate.

Principles of ecosystem management

There is a large body of literature outlining numerous principles of ecosystem management and their applications. The first step to creating better brucellosis control policies is to select a few of these principles that are crucial to grappling with the problem at hand. Although ecosystem management is a multi-faceted concept, because policies must be devised to fit particular ecosystems, species, diseases, and stakeholders, it is important to remember that all management approaches share certain overarching philosophies. Grumbine's (1994) definition is useful as a summary of these larger goals: "Ecosystem management integrates scientific knowledge of ecological relationships within a sociopolitical and values framework toward the general goal of protecting native ecosystem integrity over the long term". We have selected three management principles, drawn from the Ecological Society of America's (ESA) report on the scientific basis for ecosystem management (Christensen *et al.* 1996), the application of which we believe to be crucial for successfully controlling brucellosis in wildlife.

Focus on intergenerational sustainability, not "deliverables"

The first principle of ecosystem management listed in the ESA report is that management must focus on intergenerational sustainability rather than on "deliverables". One area where management of wildlife in the GYE fails to adhere to this principle is in the continued presence of elk feed grounds. Wyoming is the primary source of feed grounds, with 22 of them spread across the state. Elk are also fed on the National Elk Refuge (NER) in Wyoming (Figure 2b). Montana has no feed grounds, and Idaho has very few. The stated reasons for Wyoming's widespread practice of feeding elk are: (1) to keep brucellosis-infected elk from foraging on cattle ranches and (2) to maintain consistently higher numbers of elk than the available range could support, which satisfies hunters and outfitters and brings revenue to the state – thus producing a "deliverable". This latter fact largely explains the conundrum that although elk are the greater disease threat to cattle, bison are the target of most disease control interventions, because bison do not generate substantial direct revenue for any state. However, Montana has recently initiated a program to hunt bison, and may expand it considerably, possibly leading states to view bison as more of a "deliverable" resource.

It is important to examine these assumptions, and their ramifications in terms of eradicating brucellosis in wildlife and cattle in the GYE. First, are large numbers of elk in the GYE infected with brucellosis? The answer is "yes". Among elk that winter on Wyoming's feed grounds, brucellosis prevalence – as established on the basis of blood tests indicating the presence of antibodies to the disease – averages 34% (Clause and Kilpatrick *et al.* 2002) and ranges up to 80%. This is the reason that infected elk in the GYE are seen by ecologists and wildlife biologists, if not by ranchers, as the "greatest threat to the domestic US cattle population" (Donch *et al.* 2004). However, feed grounds themselves are the root of this problem. Even among federal agencies such as the US Animal Health Association, that favor stringent control of wildlife species, there is agree-

(a) Courtesy of D House

(b) Courtesy of G Smart/USFWS

Figure 2. *(a) More than 1000 of YNP's bison were culled in 2005–06, primarily in an attempt to prevent transmission of brucellosis from bison to the cattle that graze around YNP's borders. (b) The largest wintering concentration of elk occurs on Wyoming's National Elk Refuge, where the population is maintained by artificial feeding.*

ment that without feed grounds, brucellosis would not be maintained in elk at levels that are a threat to cattle or other wildlife (Thorne and Linfield 2004). Elk that do not winter on feed grounds, as in Montana, have a brucellosis prevalence of 0–3%, and probably acquire the disease from feed-ground elk. Feed grounds create opportunities for disease transmission by concentrating large numbers of pregnant animals in winter, thus allowing *Brucella* to be shed and transmitted. In the absence of feed grounds, elk disperse in winter and give birth alone, a behavior that effectively limits transmission (Cheville and McCullough *et al.* 1998). Therefore, the first argument, that feed grounds keep infected elk away from cattle ranches, is specious, because feed grounds themselves are keeping disease levels high.

The second argument is also questionable. Is feeding elk to keep their numbers artificially high a sustainable solution to the problem of limited range? We believe not, mainly because feed grounds create conditions that could easily decimate elk numbers as a result of other diseases. Hemorrhagic septicemia has already broken out several times on feed grounds, with a 2–5% rate of mortality in elk (Roffe 2001). Potentially more devastating, however, would be an epidemic of CWD (Neff 2004). This disease occurs in a variety of ungulate species and is widespread in mule deer (*Odocoileus hemionus*) and white-tailed deer (*Odocoileus virginianus*) throughout the midwest and parts of the west (Bunk 2004), where it is also found in elk. CWD is well-established in Wyoming and has been spreading in the US and Canada faster than anticipated (Figure 3). It is still not known whether CWD is transmissible to humans through the handling and/or consumption of infected animals; to date, no animal–human transmissions of CWD has been documented. The Wyoming Game and Fish Department's (WGFD) plan to control CWD in counties closest to where the disease has already occurred is based on "monitoring the population intensively" through testing of both individual elk and samples submitted by hunters, and through the removal of elk that show clinical signs of CWD. The plan concludes, optimistically, that "large-scale culling of elk is not anticipated" (WGFD 2005). Because it can take more than 2 years for CWD-infected cervids to show clinical signs (Bunk 2004), this management strategy cannot stop the spread of the disease once it hits feed grounds. CWD, which is 100% fatal in infected ungulates, has now been found near Thermopolis, less than 50 miles from the nearest Wyoming feed grounds (WGFD 2005).

We also challenge the second rationale for feed grounds – to maintain higher numbers of elk. It is unclear whether reducing or eventually eliminating feed grounds will cause greater elk mortality than an epidemic of CWD on feed grounds. A wide range of disease ecologists and WGFD's own agency officials are in agreement that CWD will eventually reach Wyoming's feed grounds, even if elk mortality figures are still hypothetical. Estimates of the proportion of any given population that will eventually become infected with CWD range enormously; 30–50% is considered a conservative estimate. According to analyses by the Greater Yellowstone Coalition, Wyoming's own agency reports place the number of fed elk, including those on the NER, at about 20 786, or roughly 22% of the estimated 93 506 elk wintering in Wyoming (Dorsey 2004). This is about 16% higher than the state's management objective. Therefore, even if every feed ground were to be removed simultaneously and every single elk that had fed on it died in the first winter, the state would be only 6% below its target number of animals. Wisconsin, which had no state feed grounds to help spread disease, destroyed 40 000 deer in 2003, in an attempt to slow CWD transmission (Bunk 2004). Officials in Idaho have chosen to search for sustainable solutions for keeping elk numbers high, estimating that the state has reduced the total number of fed elk to about 850 animals per year, or 0.7% of a total of the approximately 125 000 elk that winter in the state (Drew 2002). Idaho has also increased elk winter range through conservation easements, seeding some existing habitat with better elk forage, and trapping elk that habitually return to feeding areas and moving them to suitable winter range. Montana and Idaho have not, so far, identified CWD in wild cervids, although it is almost certain that the disease will show up in these states eventually. However, the effects on wild cervids will probably be less severe in states that are not unnaturally concentrating animals by means of their feeding practices.

The most practical and publicly acceptable way to shut down Wyoming's feed grounds is to slowly phase them out, while protecting existing winter habitat and migration corridors (and increasing them where possible). Wyoming's creation of the State Wildlife Trust Fund to acquire strategic habitat is a step in the right direction. Other groups have also submitted proposals that detail how such a phase-out might be done, including estimates of how many elk can be supported on existing forage (Dorsey 2004). A slow phase-out will avoid the potential problem of large numbers of seropositive elk seeking food on ranches, and would also avoid a sudden population crash (Table 1).

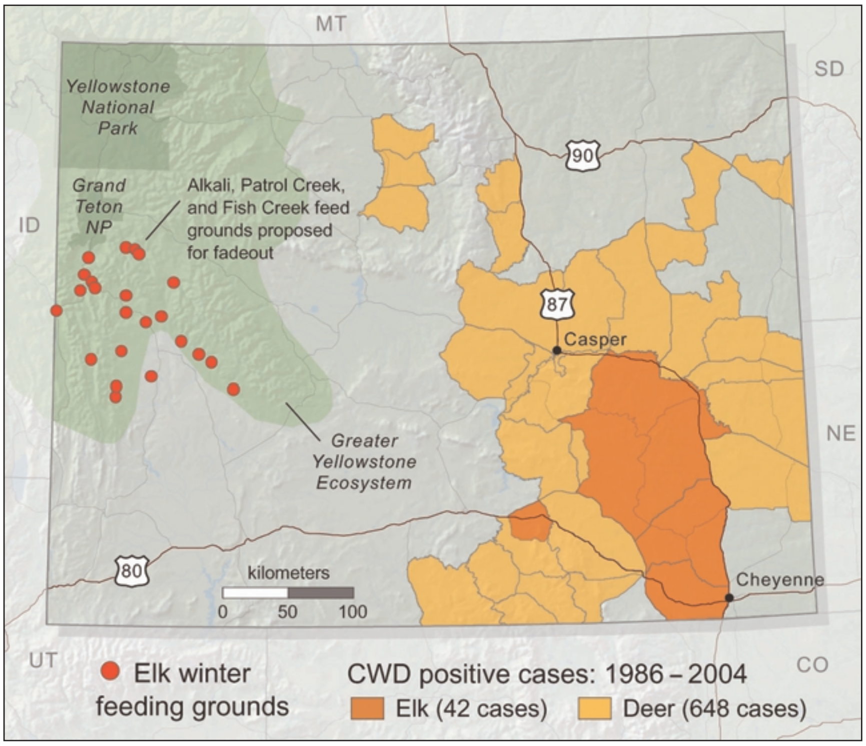


Figure 3. *Elk winter feed ground locations and positive cases of CWD in elk and deer in Wyoming, as reported by hunt area 1986–2004. Data provided by Wyoming Game and Fish Department.*

"Sound ecological models" and "context and scale"

The concepts of sound ecological models and context and scale are closely related; failure to apply them properly to management interventions may explain in large part why brucellosis prevalence in wildlife has not declined. Both principles will be discussed in the context of the two primary interventions to control wildlife brucellosis in the GYE: test-and-slaughter and vaccination.

Test-and-slaughter

Test-and-slaughter as a disease control method involves serology testing for *Brucella* antibodies, and then culling seropositive individuals. Several problems need to be addressed. First, how reliable is the test? There are several tests available, but on average, about 54% of bison that test positive have no active infection that can be determined on postmortem tissue culture (Roffe and Olsen 2002). This is a low "true positive" for a screening test. In addition, the policy of killing all serologically positive animals may be removing animals that have successfully cleared the infection and are most likely to be resistant (Gross *et al.* 2002). Existing serology can only determine exposure, although a very high or "hot" antibody titer may be indicative of an active infection. However, test-and-slaughter policy is based on two concepts: *Brucella* is

Table 1. Management goals to reduce brucellosis in elk*

Short term	• Begin phase out of three Gros Ventre feed grounds. • Assess winter habitat and begin habitat improvement measures with support of State Wildlife Trust Fund.
Medium term	• Complete phase out of at least three feed grounds, and begin second round of phase-out, including cessation of feeding on the NER. • Protect and possibly enhance existing winter habitat; make additional winter habitat available where possible.
Long term	• End routine feeding of elk anywhere in the GYE, except on an emergency basis, as outlined in plans for big game species in Idaho, and possibly the Gros Ventre Valley east of Jackson Hole.

*For all tables, "short term" is defined as within the next 4 years, "medium term" as within 10 years, and "long term" as within 25 years.

an intracellular bacterium, so even bison with low titers may be harboring bacteria that could later cause the animal to become infectious; and, screening is performed to protect cattle, so killing some uninfected bison is acceptable.

Second, can a wildlife disease control policy succeed when the policy's methods and scale were borrowed, but not adapted, from livestock disease control policies? Test-and-slaughter was introduced in the 1930s, as part of a clearly stated New Deal policy to (1) eliminate brucellosis and tuberculosis in cattle (and hogs), and (2) keep the price of beef and pork high by slashing the number of animals that reached market (US Department of Agriculture 1934). Because the brucellosis vaccine was (and still is) imperfect, and lowering the number of cattle was considered desirable, these tools were effective in substantially reducing brucellosis prevalence in livestock. Today, although few cattle herds test positive, herd depopulation for brucellosis control is still used, and most ranchers prefer it to quarantine because they receive financial compensation for slaughtered animals. However, herd depopulation is not a realistic tool in wildlife management, particularly in elk, as they are so numerous. Test-and-slaughter is therefore being applied on a much smaller scale than the one for which it was designed. The policy has been carried out most frequently in Montana, where large numbers of bison have been killed, but still less than half the population in any given year. It has also been implemented on a very limited basis for elk in Idaho, and was used on Wyoming's Muddy Creek feed ground in winter 2005–2006, as part of a 5-year pilot program that WGFD officials claim will reduce brucellosis prevalence through the slaughter of no more than 10% of that herd (Gearino 2005). The Muddy Creek program proposed construction of a large fence to corral elk, and similar programs were planned for other feed grounds. A lawsuit recently filed by three environmental groups against the WGFD, on the grounds that the analysis required by the National Environmental Policy Act has not been done, is challenging both the test-and-slaughter program and the construction of a large fence. However, there has been little discussion of the "10% reduction maximum", or its basis in principles of disease ecology.

Here, it is necessary to examine some modeling specifics to understand how wildlife brucellosis control policies have failed to incorporate the "sound ecological models" aspect of ecosystem management into test-and-slaughter programs.

Two important modeling projects examining brucellosis ecology have both concluded that management plans that remove small to moderate numbers of animals (10–25% of a population) cannot control brucellosis and will probably exacerbate disease spread by removing recovered animals (Gross *et al.* 2002; Dobson *et al.* unpublished). Nevertheless, this is exactly what is being done in test-and-slaughter programs. It is difficult to avoid the conclusion that sound ecological models are being ignored. At Princeton University, Dobson and colleagues have been modeling brucellosis in the GYE for a decade; they have developed models, using newer data, that indicate that test-and-slaughter in YNP's bison as currently applied seems to maximizes reduction in bison numbers while minimally reducing brucellosis, if at all. These new models suggest that eradication using test-and-slaughter would require over 50 years as well as near-elimination of the herd. (Dobson *et al.* unpublished). Removing recovered animals from the population, particularly when they constitute up to half the animals slaughtered, is a poor disease control policy because keeping resistant animals in the population reduces disease transmission, just as vaccination does. In small-scale test-and-slaughter programs, "the proportion of highly infectious animals in the population can actually rise...Transmission efficiency is therefore high relative to a population not subject to test-and-slaughter, and the rate of increase in the number of infected animals is very high" (Gross *et al.* 2002). In the UK, studies on the efficacy of badger culling to prevent tuberculosis in that species (on the grounds that badgers can transmit the disease to cattle) showed similar results (Donnelly *et al.* 2003). In Montana, which has the longest standing test-and-slaughter program, seroprevalence in and around YNP has risen from 40% in the mid-1980s to a fairly constant 45–50% through to the present (Cheville and McCullough 1998). Officials in Wyoming plan to remove no more than 10% of the Muddy Creek elk herd, yet, in direct contradiction to available models and historical evidence, the Director of Veterinary Services for WGFD stated recently that a 10% removal "could cause a rapid drop off in infected elk" (Gearino 2005). In Idaho, which has shown a slight decline in brucellosis prevalence in its problem herds, it is impossible to credit the improvement to test-and-slaughter because the state has also taken other brucellosis control measures (see above). We therefore conclude that existing disease models and historical evidence indicate that using test-and-slaughter in YNP's bison on a scale that would be effective would be extremely expensive, unacceptable to the public (based on the controversy that surrounds the amount of culling done in elk and bison now), and highly questionable as a management practice that strives to maintain ecosystem integrity (Table 2).

Vaccination

Vaccination programs in wildlife have suffered from similar problems of context and scale, but are possible on a wildlife-appropriate scale if well thought out and modeled beforehand. Nevertheless, they are challenging and often expensive. Available vaccines were designed for cattle, and are less effective and harder to deliver to wildlife, particularly elk. As a result, debate about the usefulness and ethics of vaccinating wildlife for brucellosis has raged for many years. We will not discuss vaccination in elk in depth here, because as noted above,

Table 2. Goals to assess current test-and-slaughter programs for sustainability and effectiveness

Short term	• Use Muddy Creek's test-and-slaughter program and the Gros Ventre feed ground phase-out for a side-by-side comparison of brucellosis control methods, by collecting data on brucellosis prevalence in the two herds and comparing them over a 5-year period. • Collect additional data from the Gros Ventre feed grounds concerning where elk from closed feed grounds go, how they use available winter range, and when or if they seek food on cattle ranches. Proposals to gather this information have been put forth elsewhere (Dorsey *et al.* 2004). • No additional elk slaughter programs on feed grounds until success or failure to control brucellosis in the Muddy Creek herd through test-and-slaughter has been adequately assessed. • Divert money from federal and state budgets now used for culling and quarantining animals and use it to increase funding for research into improved serology test.
Medium term	• Adjust number and scale of test-and-slaughter programs, depending on efficacy as shown by initial data collection. • Add in projections from models to assess the utility of test-and-slaughter in controlling brucellosis on realistic scales
Long term	• No test-and-slaughter programs without sound data generated by disease models showing that such measures work to control disease at the scale at which they are being applied.

phasing out feed grounds would obviate the need to vaccinate in this species. However, it is worth noting that despite Wyoming's use of brucellosis vaccine Strain 19 on feed grounds, data indicate that it does not prevent brucellosis infection in elk, but may slightly reduce numbers of abortions (Elzer *et al.* 2003).

Vaccination of bison around YNP's borders and at the Stephen's Creek capture facility is ongoing, and management plans will likely include widespread vaccination of bison in the park (Wallen *et al.* 2003). While researchers have argued amongst themselves about the level of efficacy of the vaccine (RB51) used in bison and cattle, agreement has finally been reached that RB51 diminishes brucellosis infection sufficiently to justify its use. Steven Olsen and colleagues at Iowa State University have shown that, in bison, RB51 provides protection against abortion or fetal infections that is "only slightly less than that reported in comparable cattle studies (81% and 88%, respectively)" (Olsen *et al.* 2003). Olsen has continued to gather data on the efficacy of RB51 in bison and has shown that hand vaccination provides reasonable protection against abortion (77% protection in vaccinates vs 32% in controls) and against infection in fetal and uterine tissue (15% protection in vaccinates vs 0% in controls; Clark *et al.* 2005). The new Interagency Bison Management Plan states that RB51 meets the necessary safety criteria for use and demonstrates sufficient efficacy in bison to call for an environmental impact statement to evaluate the "consequences of bringing a remote vaccination program on line throughout Yellowstone Park" (Clark *et al.* 2005).

Since vaccination in bison has already begun, and will probably be expanded rather than abandoned, future management strategies must include vaccination programs that are devised and carried out at appropriate scales. Three issues are important to mention in connection with wide-scale vaccine use: modeling, remote vaccination, and research and development. Gross *et al.* (2002) conclude from their models that small-scale vaccination will not work, but that vaccine use in bison could eradicate brucellosis within several decades if 40–50% of bison were consistently vaccinated. If large-scale test-and-slaughter was used synergistically, the process would be faster (Gross *et al.* 2002). However, Dobson *et al.*'s (unpublished) new models indicate that vaccination alone, with no use of test-and-slaughter, could eradicate brucellosis in 30 years by inoculating 20% of the females in a herd with a vaccine that is only 50% effective and lasts for a year. This percentage declines if the vaccine efficacy is increased (Dobson *et al.* unpublished). Again, substantial portions of the population must be vaccinated for this model to apply.

One of the reasons that vaccination has been limited in scope is the lack of a remote delivery system. However, there has been progress in this regard. Collaborative research between YNP and Colorado State has resulted in a new method of encapsulating the vaccine for remote (ballistic) delivery. Olsen's studies have also shown that protection against experimental challenge with *Brucella* was not significantly different in hand versus remote vaccination (Clark *et al.* 2005). Effective and cost-effective remote delivery systems would be preferable to hand vaccination for large-scale use in bison, since hand vaccination is time consuming, labor intensive, and stressful to the animals.

Finally, because a vaccine with low or medium efficacy in wildlife will not succeed in controlling brucellosis in the long term, without the additional use of herd depopulation, research and development of a better vaccine is urgently needed. The basic brucellosis vaccines now available have changed little in 60 years, despite enormous progress in the field of vaccine technology. Some of the results of this progress must be brought to bear on developing a better brucellosis vaccine; DNA vaccines are among the most promising, and several different projects are ongoing (Table 3).

Adaptability and accountability

In the ESA report, the authors emphasize adaptability and accountability, primarily to stress the importance of treating management strategies and goals as hypotheses

Table 3. Goals to ensure success of bison vaccination as a management strategy

Short term	• Begin widespread use of RB51 as soon as an environmental impact statement is complete to reach target goals suggested by Dobson *et al.*'s (unpublished) models, using hand vaccination until remote system is available. • Monitor herd seroprevalence through blood sampling and postmortem culture from samples submitted by hunters as well as randomly. • Increase funding for research to develop new vaccines with higher efficacy in bison and for remote delivery systems.
Medium term	• Aggressively vaccinate bison using new, remote vaccines until brucellosis levels fall to less than 5%, as identified by new serology techniques, at which point vaccination is scaled back to levels determined by modeling to keep disease at less than 4% prevalence.
Long term	• Use vaccination only as necessary, such as during disease outbreaks or during harsh winters, when more bison might leave YNP, and not as part of routine wildlife management programs.

that must be tested through research and monitoring programs and subsequently adapted (Christiansen 1996). Thus far, however, political will has played a far greater role in brucellosis control in elk and bison than has data gathered from monitoring programs. This statement is based on the fact that brucellosis control strategies in elk and bison have changed little in the past 10 years, despite evidence that seroprevalence is not being reduced in these populations, and that elk are the primary spillover reservoir for the disease.

The report also explains that inherent in the concept of accountability and adaptability are the ideas that management "must be informed by the best models of ecosystem functioning" and that natural resource management is experimental in nature. The fact that the lead agency for control of brucellosis in bison in Montana, where the majority of bison interventions take place, is the Montana Department of Livestock (DOL) has been detrimental to the application of these principles. First, livestock agency staff are not well-trained in ecological principles. Second, livestock systems are inherently much more static than the ecosystems in which wildlife function and thus it is difficult for DOLs to respond to dynamic systems in order to manage ecosystems successfully. We believe that the Montana DOL should therefore share authority with wildlife agencies on brucellosis issues. Wyoming's Department of Livestock has shared management authority in the counties surrounding YNP with appropriate wildlife agencies; Idaho's policy is more similar to Montana's than to Wyoming's, with the Idaho Department of Agriculture having removed authority over bison from the Idaho Fish and Game Department. We suggest that this decision should also be reversed (Table 4).

Conclusions

Wildlife disease management that makes crisis aversion on local scales its centerpiece, rather than focusing on proactive interventions to manage diseases on ecosystem scales, is still the norm rather than the exception. Additionally, brucellosis disease control policies in wildlife are still being formulated and implemented on the basis of sociopolitical considerations, rather than on the preponderance of scientific evidence. Brucellosis is extremely difficult to eradicate in ungulates, a taxonomic group to which it is well adapted. This fact, in addition to all the other challenges of managing diseases in wildlife, means that greater attention must be paid to the insights that the burgeoning field of landscape-scale disease ecology provides. Brucellosis has relatively little physiological impact on the wildlife species it affects; other diseases that have high fatality rates, such as CWD, will undoubtedly have more serious and less predictable consequences. If we fail to use brucellosis control to work out some basic principles for successful management of the interface between wildlife disease reservoirs, livestock, and humans, it will be a costly mistake for the health of the GYE – one of the last relatively intact ecosystems in North America.

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Table 4. Goals to incorporate adaptability and accountability into long-term bison management

Short term	• Restore Montana's Department of Fish, Wildlife and Parks as lead agency charged with managing bison within Montana; similar approach followed in Idaho.
Medium term	• Legislatively protect bison as native wildlife and/or game species in all states where they occur in the wild, and permanently handle their governance through state wildlife agencies, the National Park Service, and the US Fish and Wildlife Service. • In states that allow bison hunts, allocate a portion of hunting fees for brucellosis research. Encourage or require hunters to submit tissue for brucellosis testing, as is done with CWD testing in numerous states.

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