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Original Article

Using Structured Decision Making to Manage Disease Risk for Montana Wildlife

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ABSTRACT We used structured decision-making to develop a 2-part framework to assist managers in the proactive management of disease outbreaks in Montana, USA. The first part of the framework is a model to estimate the probability of disease outbreak given field observations available to managers. The second part of the framework is decision analysis that evaluates likely outcomes of management alternatives based on the estimated probability of disease outbreak, and applies managers' values for different objectives to indicate a preferred management strategy. We used pneumonia in bighorn sheep (*Ovis canadensis*) as a case study for our approach, applying it to 2 populations in Montana that differed in their likelihood of a pneumonia outbreak. The framework provided credible predictions of both probability of disease outbreaks, as well as biological and monetary consequences of management actions. The structured decision-making approach to this problem was valuable for defining the challenges of disease management in a decentralized agency where decisions are generally made at the local level in cooperation with stakeholders. Our approach provides local managers with the ability to tailor management planning for disease outbreaks to local conditions. Further work is needed to refine our disease risk models and decision analysis, including robust prediction of disease outbreaks and improved assessment of management alternatives. © 2012 The Wildlife Society.

KEY WORDS bighorn sheep, disease, Montana, *Ovis canadensis*, proactive management, structured decision-making.

Infectious diseases in wildlife are increasing, posing significant threats to the health of wildlife, domestic animals, and human populations and conservation of biodiversity (Daszak et al. 2000). Some of these diseases can result in massive die-offs of wildlife (Young 1994) or in significant commercial losses to livestock operations (e.g., brucellosis; Corbel 1997). Wildlife managers are generally poorly prepared to manage disease outbreaks proactively, relying instead on reactive "crisis management" (Woodroffe 1998). Deem et al. (2001) recommended that disease management for wildlife comprise health surveys, long-term monitoring, and interdisciplinary research, but did not specify how information obtained through such a program could be used to make management decisions. Decker et al. (2006) provided a model for making proactive decisions on wildlife disease management based on public and professional perceptions but did not link the model directly to a process for monitoring or predicting disease outbreaks. Biologists have used decision analysis tools to link estimated probability of disease outbreaks explicitly to decisions for managing endangered species (e.g., Maguire et al. 1987), but to our knowledge this methodology has not been applied to managing disease or its consequences in state-managed wildlife populations.

The purpose of this paper is to present a preliminary, structured decision-making framework (Keeney 2007, Gregory et al. 2012) developed for Montana Fish, Wildlife, and Parks (USA) for discerning the trade-offs of managing disease outbreaks proactively or reactively. The approach comprises 1) estimating the likelihood of a disease outbreak based on information available to managers, and 2) estimating the outcomes of management alternatives, given estimated probabilities of disease outbreak. Structured deci-

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sion-making is a transparent, stepwise process for making complex decisions that includes 1) identifying the problem to be solved, 2) determining fundamental objectives that will be used to evaluate how management actions address the problem, 3) defining alternative management actions, 4) estimating consequences for each management action based on fundamental objectives, and 5) identifying the management alternative that provides the best outcome or combination of consequences (Hammond et al. 1999). Below, we present the results of each step of the structured decision-making process.

PROBLEM STATEMENT

Montana Fish, Wildlife, and Parks has direct experience with wildlife disease events that have affected wildlife conservation and public enjoyment of wildlife resources. For the most part, Montana Fish, Wildlife, and Parks has only reacted to these major disease events and currently has no tools for determining whether taking actions to proactively prevent similar events will produce more desirable results. Future wildlife disease issues in Montana are unavoidable. Montana Fish, Wildlife, and Parks wildlife managers and biologists need risk assessment and decision analysis tools to help prioritize and allocate resources to identify and manage the risk of major disease events. These tools need flexibility in their implementation so that decisions about wildlife management and conservation remain local and community-based.

We structured our decision analysis to reflect the agency structure, the fact that wildlife diseases affect populations of particular species in particular areas, and that management decisions are made at these local scales. We therefore describe a Montana wildlife health program that has a unifying, general problem statement and overarching general objectives that are consistent with the conservation of any wildlife species or population in Montana. In practice, these general program objectives will be honed specifically for different wildlife species and health issues. Management actions and alternatives for particular wildlife species and disease issues are specific to local areas in Montana, but can be generalized into statewide categories of aggressive proactive actions, moderate proactive actions, and reactive actions (i.e., the status quo management alternative). To a large degree, the predicted and realized consequences of management actions are also likely to be specific to local areas in Montana. A set of models to predict the consequences of management actions on specific wildlife species and health issues, however, can be developed to assist in making those local and regional predictions. Employing these models across Montana using the common framework presented here will facilitate a consistent approach to the way in which local wildlife health management decisions are made. In addition to site-specific consequence predictions, value weights for objectives, trade-offs, and risk tolerance are likely to be specific to each regional wildlife biologist or program manager with responsibility for a particular population of wildlife.

FUNDAMENTAL OBJECTIVES

We identified a set of nested objectives and sub-objectives that are fundamental for a general, proactive wildlife health program in Montana:

1. Maximize wildlife population health, which includes 2 sub-objectives: maximize the probability of population persistence and minimize the probability of a disease outbreak occurring that leads to a major die-off of a wildlife population.
2. Minimize risks posed by wildlife, which includes sub-objectives to minimize risk of disease transmission to livestock and to people.
3. Minimize costs, including sub-objectives to minimize operating costs, personnel costs, and other costs associated with responding to crises.
4. Maximize public satisfaction, which includes sub-objectives to maximize both non-consumptive and hunting opportunities.

These objectives can be characterized as general objectives for wildlife management and conservation, whether we are considering wildlife health threats or other threats to wildlife conservation. In this way, we have defined a manner in which a wildlife health program can contribute to, and be integrated into, a more general wildlife management and conservation program.

To illustrate the decision structure and how the overarching Montana wildlife health program might be applied, we used pneumonia outbreaks among bighorn sheep (*Ovis canadensis*) populations as a case study for working through our decision analysis. Outbreaks of pneumonia in bighorn sheep are commonly tied to contact with domestic sheep and goats and can result in catastrophic die-offs (Foreyt and Jessup 1982, Foreyt 1989, Cassirer and Sinclair 2007, Wehausen et al. 2011). Recently, pneumonia has resulted in large die-offs within populations of bighorn sheep across the western United States, at times necessitating extensive culling efforts in an attempt to control spread of the disease. These die-offs have led to the loss of individual populations and, in some instances, meta-populations (Edwards et al. 2010). Our decision analysis begins to fulfill the management need for establishing a systematic health-monitoring and disease management program identified in the Montana Bighorn Sheep Conservation Strategy (MFWP 2009). For application to management of pneumonia outbreaks in bighorn sheep, we narrowed the objectives to reflect the management context unique to bighorn sheep:

1. Maximize the probability of herd persistence, which we propose to measure by determining whether populations are within objectives or not, as defined by the Montana Bighorn Sheep Conservation Strategy (MFWP 2009). The persistence of populations depends on social tolerance as much as biological carrying capacity and stochastic persistence risks associated with small populations; Montana Fish, Wildlife, and Parks has already established population objectives that consider these factors.

2. Minimize costs, including operational costs, personnel costs, and crisis response costs. We will measure this objective using projected costs incurred, in dollars and/or personnel time, over a 10-year period.
3. Maximize public satisfaction, including viewing and hunting opportunities. Public viewing opportunities will be measured using the criteria of whether populations are within objective or not. Public hunting opportunity will be measured by the predicted number of licenses issued over a 10-year period.

ALTERNATIVE ACTIONS

Alternative management actions are specific to each population of animals, and are decided upon by regional wildlife managers and biologists working with stakeholders in local communities. Management actions for any wildlife disease or health issue will be unique to the disease, wildlife species, location, and social context in question; no general approach will work for all situations. For managing outbreaks of pneumonia within a bighorn sheep herd, alternatives focus on the relative effort invested in maintaining physical separation of bighorn sheep and domestic sheep and goats. Possible actions managers and biologists could take to manage a major disease event fall within 3 categories:

1. *Reactive management actions*. This involves no attempt to proactively limit interactions between wild and domestic sheep and goats. Population declines lead to populations failing to meet defined objectives, allocation of staff time and resources to cull (if appropriate) sick bighorn sheep, collecting and processing biological samples, sample analysis fees, increased monitoring to detect recovery of collapsed populations, as well as the loss of viewing and hunting opportunities.
2. *Moderate proactive management actions*. These actions will be relatively low-cost and socially acceptable, specific to local circumstances, and the situation as determined by regional wildlife managers and biologists. These may include communicating with landowners or livestock producers to minimize contact between bighorn sheep and domestic sheep or goats, or removing bighorn sheep that commingle with domestics.
3. *Aggressive proactive management actions*. These actions will be more expensive, potentially less socially acceptable, and, again, specific to local circumstances. Actions may include fencing domestic sheep herds to limit interactions between bighorn sheep and domestic sheep or goats, or increasing male bighorn sheep harvest in order to effect a decline in the adult male:adult female ratio (thereby preventing the spread of disease by wide-ranging males during the rut).

PREDICTING THE LIKELIHOOD OF A MAJOR DISEASE EVENT

Development of predictive models for the risk of wildlife disease events would help wildlife managers in their decision-making processes. Predictive models can be standardized to apply to a particular species or wildlife disease situation, so that managers of wildlife populations across the state (or at another reasonable scale) characterize and incorporate risk into their decisions in the same manner, while continuing to apply their local knowledge of wildlife populations and site-specific management options.

To illustrate this, we developed a risk assessment model to predict the probability of a major disease event for a herd of bighorn sheep over a 10-year time horizon. We defined a major disease event as one with $\geq$50% mortality in any 1 year. The model was simple (Table 1): the probability (Pr) of a major disease event in any 1 year was a function of Pr(exposure), E; Pr(susceptibility), S; and Pr(risk of spread), R.

For our case study, we assumed E was best predicted by contact with domestic sheep and goats (primary sources of infections that lead to pneumonia outbreaks), proximity to bighorn sheep herds infected with pneumonia, and recent or historical presence of pneumonia within the bighorn sheep population. The range of potential values assigned to each cue reflected a subjective, relative weighting of importance as decided upon by the experience and expertise of our team. We defined E as the sum of the assigned values for each cue, divided by the maximum possible value for the sum (Table 1).

We assumed S could be predicted by the unweighted average of several cues, including assessments of clinical condition, habitat condition, and low recruitment of lambs (lamb mortality is high during and following pneumonia outbreaks). We estimated S as the average value (range = 0–3) assigned to each of 6 potential indicators, divided by 3, the maximum possible value for the average. Indicators for which no information was available did not contribute to the average (Table 1).

We assumed R could be predicted by the density and distribution of bighorn herds, and the observed ratio of adult males to adult females (males range much more widely than females and are thought to be important vectors for spread of disease among herds). We defined R as the sum of the assigned values for each, divided by 9, the maximum possible value for the sum (Table 1).

We defined the Pr(major disease event in any 1 yr) as the product of E, S, and R. The probability of *no* major disease event in t years is $1 - \text{Pr(major disease event in any 1 yr)}^t$. Over a time horizon of 10 years, the probability of observing at least one major event was $1–[1 - \text{Pr(major disease event in any 1 yr)}]^{10}$ (Mood et al. 1974).

Our model was constructed in a spreadsheet so that regional wildlife biologists and managers could use it to predict the impacts of their management actions on the risk of a major disease event. To do this, managers can decide which component of risk their management actions are designed to mitigate; for example, fencing domestic sheep herds is designed to reduce the exposure of bighorn sheep to domestic sheep. Managers can then predict how their management actions will affect the scores for that particular component(s) of risk, input those estimates into a new model run, and thereby predict how the risk of a pneumonia event will be affected by the proposed action. Thus, the model becomes a

Table 1. Disease risk model for estimating the probability of a major disease outbreak (i.e., $\geq$50% mortality in a population) for bighorn sheep (*Ovis canadensis*) in Montana, USA, based on estimated exposure, E, susceptibility, S, and risk of spread, R. Annual risk of a major disease outbreak $= E \times S \times R$.

Metric	Score[a]
Risk of exposure, E	If $E2 = 8$, then $E = 1$, else $E = \frac{\sum(E1, E2, E3)}{\sum(E1^{\max}, E2^{\max}, E3^{\max})}$
Contact with domestic sheep and goats, $E1$	
Highly unlikely	0
Within range of forays	2
Within $\leq$7 miles	4
Within home range	6
Contact with infected bighorn sheep, $E2$	
Highly unlikely	0
Within range of forays	2
Within adjacent herd	4
Within home range	8
Current presence of pathogens, $E3$	
Absent or unknown	0
Present in the past	1.5
Known to be present	3
Susceptibility, S	$S = \frac{\sum(S1, S2, S3, S4, S5, S6)/6}{3}$
Body condition, $S1$	Low (0), medium (1.5), high (3)
Parasite load, $S2$	Low (0), medium (1.5), high (3)
Blood parameters, $S3$	Low (0), medium (1.5), high (3)
Range measures, $S4$	Low (0), medium (1.5), high (3)
Mineral levels, $S5$	Low (0), medium (1.5), high (3)
Lamb:F ratio, $S6$	Poor (3), low (2), medium (1), high (0)
Risk of spread, R	$R = \frac{\sum(R1, R2, R3)}{\sum(R1^{\max}, R2^{\max}, R3^{\max})}$
Herd density, $R1$	
Within Montana Fish, Wildlife, and Parks objectives	0
Slightly over Montana Fish, Wildlife, and Parks objectives	1.5
Well over Montana Fish, Wildlife, and Parks objectives	3
Herd distribution, $R2$	
Normal-sized herds	0
Large herds, small natural areas	1.5
Large herds, small artificial areas	3
M:F ratio, $R3$	Low (0), medium (1.5), high (3)

[a] Scores assigned to sub-metrics are based on subjective evaluation of relative contribution to overall risk of disease outbreak.

uniform tool for managers to assess and compare alternative, local management actions and to engage stakeholders in the decision process.

To evaluate the usefulness of this model in informing management decisions, we parameterized the model for the Missouri Breaks bighorn sheep herd in eastern Montana and the Petty Creek bighorn sheep herd in western Montana (Fig. 1). We chose these herds because the herd managers were present on our team, and because they represented different disease contexts in different parts of Montana. We parameterized the model for the 3 management alternatives (reactive management, moderate proactive management, aggressive proactive management) for each herd by eliciting values from herd managers familiar with local herd conditions, as well as the knowledge of statewide technical staff regarding clinical and habitat conditions. We elicited values for calculating E, S, and R under the assumption they equated with relative probabilities.

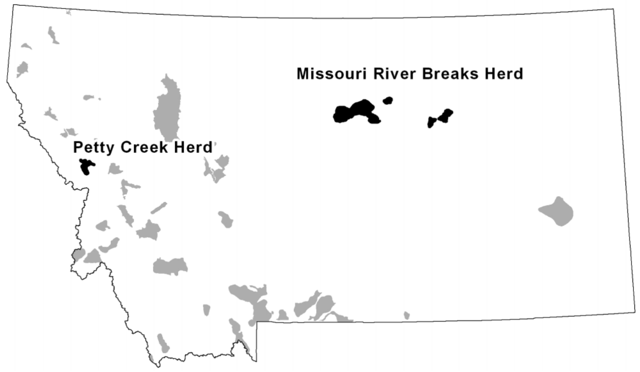

Figure 1. Locations of bighorn sheep (*Ovis canadensis*) herds in Montana, USA. Darkened polygons represent the Petty Creek herd in western Montana, and the Missouri Breaks herd in central Montana. The 2 herds experience 2 different environments affecting likelihood of major disease outbreak. The Petty Creek herd is well-connected to other infected bighorn sheep herds in the region and is regularly exposed to domestic sheep and goats. By contrast, the Breaks herd is relatively isolated from infected bighorn sheep and has little exposure to domestics due to ongoing proactive management.

DECISION ANALYSIS

For both the Missouri Breaks and Petty Creeks herds, we constructed a decision tree (Behn and Vaupel 1982; Table 2) to estimate the consequences of the 3 management alter-

Table 2. Example of a decision table with estimated consequences for 3 alternative strategies for managing disease outbreak in bighorn sheep (*Ovis canadensis*) within the next 10 years proactively, illustrated for a population of bighorn sheep living in Petty Creek, Montana, USA. The top row contains fundamental objectives, the second row contains whether objectives were to be minimized or maximized, the third row contains measurable attributes for each objective, and the fourth row the scale on which they are measured. The remaining 3 rows contain the estimated consequences under each objective in the event a major disease outbreak does and does not occur, and the "expected" or the probability-weighted average outcome, under each of the 3 management alternatives (Behn and Vaupel 1982). Probabilities of disease or no disease are estimated from the disease risk model in Table 1.

Management alternative	Fundamental objective:	Probability of persistence	Operating costs	Personnel costs	Crisis response	Viewing opportunity	Hunting opportunity
	Goal:	**Maximize**	**Minimize**	**Minimize**	**Minimize**	**Maximize**	**Maximize**
	Attribute:	**Meet population objective?**	**US$ cost/ 10 yr**	**Person-days/ 10 yr**	**US$ cost/ 10 yr**	**Meet population objective?**	**No. licenses sold/10 yr**
	Scale:	**1 = yes, 0 = no**	**US$K/10 yr**	**Days**	**US$K/10 yr**	**1 = yes, 0 = no**	**No./10 yr**
Aggressive, proactive	Pr(disease) = 0	0	105	220	80	0	100
	Pr(no disease) = 1.0	1.0	105	220	0	1.00	200
	Expected outcome[a]	0.9	105	220	8	0.90	190
Moderate, proactive	Pr(disease) = 0.2	0	100	170	80	0	75
	Pr(no disease) = 0.8	1.0	100	170	0	1.00	150
	Expected outcome	0.8	100	170	16	0.80	135
Reactive	Pr(disease) = 0.6	0	0	0	80	0	75
	Pr(no disease) = 0.4	1.0	0	0	0	1.00	150
	Expected outcome	0.4	0	0	48	0.40	105

[a] Expected outcome = [consequence of disease × Pr(disease)] + [consequence of no disease × Pr(no disease)].

natives. Probabilities describing the chance of 2 possible states—the occurrence or non-occurrence of a major disease event within 10 years—were used to estimate "expected consequences," or the average of the consequences with and without disease weighted by the probability of whether a major disease event would occur under each management alternative (Table 2). Then we used these expected or probability-weighted outcomes to assess the managers' preferences for balancing between their objectives, using the Simple Multi-Attribute Rating Technique (Edwards 1971, Goodwin and Wright 2004). For both herds, we normalized the expected consequences across the range in our alternatives for each objective and weighted them according to the value judgments of these local bighorn sheep herd managers, elicited using swing weighting (von Winterfeldt and Edwards 1986). We then aggregated judgments using simple weighted summation to characterize the overall value of each alternative (Table 3).

Our analyses for the Petty Creek and Missouri Breaks herds provided a good test of the ability of this decision

Table 3. Example of a Simple Multi-Attribute Rating Technique decision analysis evaluating 3 management alternative to proactively managing disease outbreak in bighorn sheep (*Ovis canadensis*; no proactive management, moderate proactive management, and aggressive proactive management), illustrated for a population of bighorn sheep living in Petty Creek, Montana, USA. The top row contains fundamental objectives, the second row contains whether objectives were to be minimized or maximized, and the third row contains measurable attributes for each objective. The fourth row contains relative weights assigned to each objective by the manager of the Petty Creek herd, estimated by swing weighting based upon the range of expected outcomes for each objective (Table 2). Weights were determined subjectively by decision-makers and sum to 1. The final 9 rows contain the expected outcomes, their normalized score, and their weighted score for each of the fundamental objectives under each of the 3 management strategies and in the last column the sum of normalized, weighted scores, indicating relative support of the decision analysis for each management alternative (Goodwin and Wright 2004).

Management alternative	Fundamental objective:	Probability of persistence	Operating costs	Personnel costs	Crisis response	Viewing opportunity	Hunting opportunity	Summed normalized, weighted scores
	Goal:	**Maximize**	**Minimize**	**Minimize**	**Minimize**	**Maximize**	**Maximize**	
	Measurable attributes:	**Meets population objective?**	**US$ cost/ 10 yr**	**Person-days/ 10 yr**	**US$ cost/ 10 yr**	**Meets population objective?**	**No. licenses sold/10 yr**	
	Weight:	**0.21**	**0.15**	**0.14**	**0.19**	**0.15**	**0.18**	
Aggressive, proactive	Expected outcome[a]	0.9	105	220	8	0.9	190	
	Normalized score	1.00	0.00	0.00	1.00	1.00	1.00	
	Weighted normalized score	0.21	0.00	0.00	0.19	0.15	0.18	0.72
Moderate, proactive	Expected outcome	0.8	100	170	16	0.8	135	
	Normalized score	0.80	0.05	0.23	0.80	0.80	0.35	
	Weighted normalized score	0.17	0.01	0.03	0.15	0.12	0.06	0.53
Reactive	Expected outcome	0.4	0	0	48	0.4	105	
	Normalized score	0.00	1.00	1.00	0.00	0.00	0.00	
	Weighted normalized score	0.00	0.15	0.14	0.00	0.00	0.00	0.28

[a] From Table 2.

analysis system to assist managers in making decisions. The 2 herds experience very different environments affecting the likelihood of disease outbreaks. The Petty Creek herd is at a high-risk of exposure to domestic sheep and goats on developed private lands. By contrast, the Missouri Breaks herd is not currently exposed to infected bighorn sheep herds, and active management to prevent association with domestic sheep in the region is ongoing. To be credible as a tool for assisting decision-making, our disease risk model and decision analysis tools would need to distinguish the risk of a major disease event for both herds, as well as point to management actions that reflect these different levels of risk.

Given input by species experts and managers and assuming current management practices continue, the risk analysis model predicted the probability of a major disease event within the next 10 years to be 0.56 for the Petty Creek herd and 0.18 for the Missouri Breaks herd. The decision analysis for the Petty Creek herd provided strong support for aggressive proactive management, modest support for moderate proactive management, and little support for reactive management (Table 3; Fig. 2). By contrast, the analysis for the Missouri Breaks herd showed strong support for either aggressive or moderate proactive management, with little support for reactive management (Fig. 2).

DISCUSSION

To facilitate the development of a wildlife health program for the state of Montana, we used a structured decision-making approach to define the problem, establish fundamental objectives, identify alternative management actions, and define metrics of success. During this process we developed a model to estimate the probability of a disease outbreak and linked this model with decision analysis that allows managers to proactively evaluate likely effects of alternative actions on both disease risks and fundamental management objectives. Carefully structuring the analysis led to substantial progress that would not have been possible otherwise. The major value of this approach came from the focused thinking and debate on the problem statement, the objectives of the program, and the discussion of the actual management alternatives. This focused thinking led to clarity on how the decision needed to be framed, and how a program like this could be structured to mesh with an agency structure that promotes local, community-based wildlife conservation rather than centralized decision-making authority. This clarity would not have been possible without carefully delineating the various elements of the actual decision.

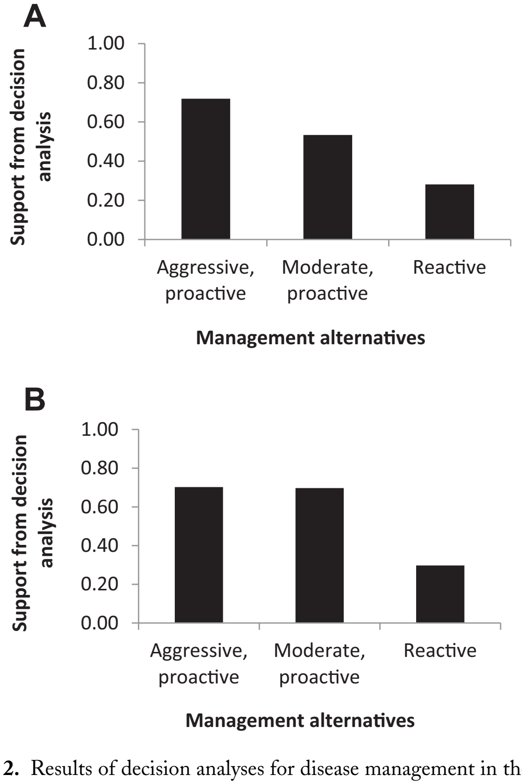

Figure 2. Results of decision analyses for disease management in the Petty Creek (A) and Missouri Breaks (B) herds of bighorn sheep (*Ovis canadensis*) in Montana, USA. Graphs illustrate relative support for the 3 management alternatives between the 2 herds.

We designed a framework that assists regional managers in reaching local decisions reflecting statewide wildlife conservation objectives. The framework we developed addresses 2 of the most challenging components of decision-making in wildlife conservation and disease management in particular: the inherently probabilistic nature of disease events and effects, and the inherent tensions among Montana Fish, Wildlife, and Parks's fundamental objectives. To this end, we employed a combination of modeling and decision analysis tools, including a predictive risk model, a decision tree, and Simple Multi-Attribute Rating Technique trade-off analysis and management alternatives scoring.

Although we have explored the value of the more technical aspects of this decision framework (e.g., models used to predict the consequences of alternative management actions relative to meeting objectives), their full potential has not yet been fully realized. To use the model we developed for predicting the risk of major disease events in bighorn sheep herds to inform decisions about bighorn sheep management, more focused work on model development and reliability is required. This technical work is appropriate now that the decision and program have been framed with clarity, and there is now a strong likelihood that such predictive model(s) will be useful. Predictive model(s) will be valuable to the extent they help managers make decisions that are better for having used the models than they would have been otherwise. Work to increase the accuracy of predictive models is warranted if it improves the decision analysis, affecting not only the consequence predictions but the indicated choice among management options and confidence those actions will achieve management's fundamental objectives.

In our bighorn sheep model, for example, the measurable attributes relative to the population objectives are likely oversimplified. Currently, these attributes are constructed as thresholds, where a value of 1 indicates that the population is within objective bounds, and a value of 0 indicates otherwise. Populations that fall marginally outside objective bounds are thus assigned zero value, which may prove unrealistically simple for assessing trade-offs that wildlife managers need to make. In future application, the attribute may be constructed such that all population sizes within objective bounds receive the highest possible value, while population sizes outside of the objective range are scored lower the further from the objective bounds they are (*sensu* Keeney 2007). Similarly, we used population objectives as measurable attributes for 2 fundamental objectives; future application should identify a distinct and more focused attribute for public satisfaction instead of duplicating the population persistence attribute. This should allow managers the flexibility needed to make trade-offs in management decisions when necessary.

Uncertainty within the risk analysis model also needs to be addressed. The illustrative model we developed for bighorn sheep is a simple linear additive model built on expert judgment, which although generally robust to uncertainty (Dawes 1979, Dana and Dawes 2004), could be improved substantially. Predicting disease outbreaks is challenging, particularly when the tools (e.g., collection and analysis of blood or other tissues) for detecting contributing factors are limited. Work is needed to do the following:

1. Coordinate with other experts in Montana to ensure all of the key factors influencing probabilities of pneumonia outbreaks are captured in the modeling framework, and factors used to predict probabilities of pneumonia outbreaks are measured and weighted relative to each other in an epidemiologically credible manner.
2. Use statistical model(s) to predict disease outbreaks using the available historical data, in order to calibrate the model(s) to real observations before the model(s) receive widespread use to predict new observations.
3. Conduct sensitivity analyses of the various components of the risk model as it is applied to the management of bighorn sheep populations. The risk model contains several major assumptions; for example, it assumes a linear relationship between risk scores and the probabilities of exposure, susceptibility, and spread. The sensitivity analysis needs to reveal the extent to which these critical assumptions affect overall predictions of the probability of disease outbreaks and resulting choice of preferred management actions. The sensitivity analysis can inform how much effort is warranted toward improving the models, including identifying more nuanced and accurate relationships between risk and exposure than the simple linear relationship assumed in the case study.
4. Design a complementary monitoring program that directly inform the factors included in the risk analysis model, allowing adaptive improvement of the model(s) through learning as these tools are used to inform decisions.

Ultimately, the Montana wildlife health program must be structured as the agency is structured. To be effective and sustainable it should be fully integrated into the broader wildlife conservation program via a focus on unifying wildlife conservation objectives. The overall mission of the wildlife health program can be defined at a statewide level to be focused on managing wildlife health issues to ensure the conservation of wildlife species, as we have done. This context is imperative because the mission of state and federal wildlife agencies is more focused on fundamental wildlife conservation objectives than on elimination or limitation of wildlife disease. By using this framework, undesirable consequences of wildlife disease for effective wildlife conservation need to be identified before resources are expended to manage disease transmission or monitor the disease. Undesirable consequences of wildlife disease are not necessarily universal, for example parasites and diseases can have fundamental roles in ecosystem function (Eviner and Likens 2008), and in many cases the ecological consequences of diseases are virtually unknown (Deem et al. 2008). In addition, some actions designed to limit disease spread will require trade-offs for objectives valued for other aspects of wildlife conservation (e.g., reductions in wildlife population sizes). Without placing a wildlife health program in a decision analysis context such as Simple Multi-Attribute Rating Technique, such trade-offs could not be made explicit. Objectives may be honed to deal with particular species or health issues, as we have exemplified in our case study concerning bighorn sheep die-offs, but the focus on wildlife conservation should remain in these refined objectives.

Both the disease risk model and decision analysis tools include assumptions and uncertainty; reducing this uncertainty would benefit this decision-making process. First and foremost, we developed models for predicting and managing disease outbreak in bighorn sheep as a case study example of how a Montana wildlife health program might be structured. Obviously, a complete wildlife health program for the state would need to be expanded to encompass diseases such as brucellosis, chronic wasting disease, etc., and other wildlife species that are affected by health issues. Whereas the general framework described here should apply to all cases, developing objectives, management alternatives, and appropriate models for each situation will require focused work to construct individual, well-designed adaptive-management programs. These programs will necessarily be specific to species and health issues under the general framework we provide, and will allow predictions to be improved over time so that the models become more reliable and useful as they are put to use informing actual decisions with follow-up monitoring.

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