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Commentary

Structured Decision Making for Managing Pneumonia Epizootics in Bighorn Sheep

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ABSTRACT Good decision-making is essential to conserving wildlife populations. Although there may be multiple ways to address a problem, perfect solutions rarely exist. Managers are therefore tasked with identifying decisions that will best achieve desired outcomes. Structured decision making (SDM) is a method of decision analysis used to identify the most effective, efficient, and realistic decisions while accounting for values and priorities of the decision maker. The stepwise process includes identifying the management problem, defining objectives for solving the problem, developing alternative approaches to achieve the objectives, and formally evaluating which alternative is most likely to accomplish the objectives. The SDM process can be more effective than informal decision-making because it provides a transparent way to quantitatively evaluate decisions for addressing multiple management objectives while incorporating science, uncertainty, and risk tolerance. To illustrate the application of this process to a management need, we present an SDM-based decision tool developed to identify optimal decisions for proactively managing risk of pneumonia epizootics in bighorn sheep (*Ovis canadensis*) in Montana. Pneumonia epizootics are a major challenge for managers due to long-term impacts to herds, epistemic uncertainty in timing and location of future epizootics, and consequent difficulty knowing how or when to manage risk. The decision tool facilitates analysis of alternative decisions for how to manage herds based on predictions from a risk model, herd-specific objectives, and predicted costs and benefits of each alternative. Decision analyses for 2 example herds revealed that meeting management objectives necessitates specific approaches unique to each herd. The analyses showed how and under what circumstances the alternatives are optimal compared to other approaches and current management. Managers can be confident that these decisions are effective, efficient, and realistic because they explicitly account for important considerations managers implicitly weigh when making decisions, including competing management objectives, uncertainty in potential outcomes, and risk tolerance. © 2016 The Wildlife Society.

KEY WORDS bighorn sheep, decision tool, disease, management, Montana, *Ovis canadensis*, pneumonia, proactive management, risk model, structured decision making.

Good decision-making is challenging but essential for conserving wildlife populations (Gregory et al. 2012, Conroy and Peterson 2013, Mitchell et al. 2013, Runge et al. 2013). Decisions, or the "pursuit of a course of action" (Howard 1966:55), in wildlife management must integrate values with science to achieve desired future conditions (Runge et al. 2013). Managers need decisions to be effective at solving the problem, yet efficient and realistic for budgetary, manpower, and social considerations. Decisions need to be transparent and defensible to supervisors, employees, and constituents. Decisions also need to take into account institutional values, uncertainty, and risk tolerance. If decisions are made locally or repeatedly throughout an organization, a consistent decision-making process can be important. Identifying an optimal decision that accounts for all of these considerations, however, is challenging. An informal decision-making process may ignore or leave implicit potential assumptions, uncertainties, values, and priorities that may require explicit consideration to identify optimal decisions. Although informal decision-making is often adequate for relatively simple problems, a formal decision-making process can have great utility for more complex issues by explicitly integrating diverse, complex, and contradictory considerations that make

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identification of optimal solutions difficult (Runge et al. 2013). Structured decision making (SDM) is a decision analytic method that breaks decision-making into logical components of identifying the management problem, defining objectives for solving the problem, developing alternative approaches to achieve the objectives, and formally evaluating which of the alternatives is most likely to accomplish the objectives (Gregory et al. 2012, Conroy and Peterson 2013, Mitchell et al. 2013, Runge et al. 2013). Although application of SDM for a management issue may require potential upfront investments in time, funding, and training, these are generally far less costly than the consequences of a poorly made decision.

Despite its potential to managers and a growing interest in the application of SDM for management issues (Runge et al. 2013), there is a paucity of examples in the wildlife literature of real-world utility of the SDM process. To demonstrate the value and application of SDM, we illustrate its use by Montana Fish, Wildlife and Parks (MFWP) to make decisions for proactively managing pneumonia epizootics in bighorn sheep (*Ovis canadensis*). Herd health has direct implications for achieving management objectives, yet the probabilistic nature of epizootics makes it difficult to integrate health with decision-making for broader management programs without a formal decision-making process (Mitchell et al. 2013).

Pneumonia is a critical problem for management of bighorn sheep throughout their range in North America (Gross et al. 2000, Cahn et al. 2011, Wehausen et al. 2011, Cassirer et al. 2013, Plowright et al. 2013). Pathogen exposure from domestic to bighorn sheep is the only supported hypothesis in experimental trials (Wehausen et al. 2011). Mortality during epizootics can exceed 80%, and subsequent pneumonia outbreaks may continue for decades and lead to chronically low lamb recruitment and, potentially, extirpation (Enk et al. 2001, MFWP 2010, Cassirer et al. 2013, Plowright et al. 2013, Sells et al. 2015). In Montana alone, out of approximately 52 herds, there have been $\geq$22 epizootics of $\geq$25% mortality from 1979–2013, 15 of which resulted in >50% mortality (MFWP 2010, Sells et al. 2015). At least 11 epizootics occurred between 2008–2013. Impacts of epizootics have included total extirpation of 1 herd and poor recovery in $\geq$3 others, despite up to 30 years of recovery efforts by MFWP.

Commonly, a lack of tools to predict and proactively manage risk of wildlife diseases leads to a reactive crisis management response to disease events, including for pneumonia epizootics in bighorn sheep (Woodroffe 1999, Edwards et al. 2010, Mitchell et al. 2013, Sells et al. 2015). Intensive, costly management may be required to help herds recover, including culling sick sheep (Edwards et al. 2010), and herd augmentation (MFWP 2010) or reintroduction (Singer et al. 2000) using sheep translocated from other herds. Such reactive crisis management may ultimately prove ineffective for herd recovery; proactive management designed to prevent epizootics from occurring is strongly preferred by managers.

Pneumonia epizootics are relatively rare and difficult to predict, and managers could have varying degrees of risk tolerance to their occurrence. To make good decisions for managing epizootics proactively, managers thus need a means of better understanding and formally accounting for risk of a pneumonia epizootic. Sells et al. (2015) developed an empirical model for predicting risk of pneumonia epizootics in bighorn sheep in Montana. Through analysis of 43 herd histories in Montana from 1979–2013, Sells et al. (2015) identified 4 risk factors positively associated with probability of pneumonia epizootics within herds of bighorn sheep (Table 1): private land, weed control, neighbor risk, and density. Private land was the amount of private land in a herd's area of high risk (i.e., herd distribution plus a 14.5-km buffer), which was expected to represent risk of pathogen exposure through potential contact with domestic sheep or goats on hobby or commercial farms. Weed control was the known use of domestic sheep or goats to control weeds in a herd's area of high risk, which was expected to be associated with increased risk of pathogen exposure through potential contact with domestic sheep or goats. Neighbor risk was when a herd or a neighboring herd in the herd's area of high risk had a pneumonia epizootic since 1979, which was expected to be associated with increased risk of pathogen exposure among nearby herds. Density was medium to high density for a herd relative to its historical densities from 1979–2013; this was expected to be associated with increased risk of spread of pathogens within the herd. The model presented by Sells et al. (2015) provides a means to estimate probability of pneumonia epizootics for any herd in the state over any timeframe desired.

Estimated risk of disease, however, does not automatically suggest appropriate proactive management to reduce the risk. Simply knowing risk does not clarify what management approaches will best minimize it. Important budgetary, manpower, and social considerations also exist, along with the larger context of conservation objectives for a wildlife population or species. A decision analytic approach is therefore needed to evaluate the costs and benefits of alternative management decisions that could proactively

Table 1. Parameter estimates of the risk model (Sells et al. 2015) for pneumonia epizootics for bighorn sheep, Montana, USA. Within the herd distribution plus a 14.5-km buffer from that perimeter, private land was the effect of percentage of private land, weed control was the effect of known use of domestic sheep or goats for weed control, and neighbor risk was the effect of a previous pneumonia epizootic in the herd or a neighboring herd. Density(M) and density(H) were the effects of herd-specific relative density, defined at low, medium (M), and high (H) density relative to the herd's percentage of average density from 1979–2013.

			Credibility interval	
Parameters	$\bar{x}$	**SD**	**0.100**	**0.900**
Intercept	−6.269	0.761	−7.253	−5.344
Private land	0.433	0.239	0.130	0.740
Weed control	1.210	0.547	0.505	1.900
Neighbor risk	2.331	0.524	1.675	3.004
Density(M)	1.660	0.728	0.750	2.593
Density(H)	2.699	0.742	1.779	3.658

reduce risk of disease and account for all of these considerations.

To address these challenges, we developed a decision tool for proactively managing pneumonia in bighorn sheep in Montana based on the SDM process and following a prototype developed by Mitchell et al. (2013). Our decision tool incorporates an empirical model for predicting probability of pneumonia epizootics (Sells et al. 2015) to evaluate potential consequences of management actions. We worked with biologists and managers at MFWP to use existing information and incorporate their values, priorities, and constraints to make the process and resulting decision tool useful for MFWP staff in managing pneumonia in bighorn sheep as effectively as possible. We describe below each step in SDM used to create our decision tool and demonstrate its use. We then discuss how uncertainties and values may have influenced the decisions we identified for example herds to better understand those decisions. Our objectives were to summarize SDM for wildlife biologists and managers, demonstrate how a wildlife agency used SDM for a real management challenge, illustrate the formal incorporation of an empirically based biological model in a decision-making process, and provide a case study using SDM for making decisions on management of bighorn sheep at risk of pneumonia.

COMPONENTS OF THE SDM PROCESS AND DECISION TOOL

The SDM process deconstructs a decision into logical components (Fig. 1; Gregory et al. 2012, Conroy and Peterson 2013, Runge et al. 2013). The problem statement describes the management issue to be resolved by making a decision, fundamental objectives represent what ideally would be accomplished by a good decision, and alternatives are the potential actions that could be taken to meet the fundamental objectives. Decision analysis involves evaluating consequences and trade-offs among alternatives to identify the one most likely to yield optimal results. Mitchell et al. (2013) presented these steps for proactively managing pneumonia epizootics in bighorn sheep from a workshop held with MFWP managers and biologists. In 2014, we met with a working group consisting of different MFWP biologists and managers to revisit the Mitchell et al. (2013) work and complete the decision tool. We then determined the utility of our tool in helping members of the working group identify optimal decisions for herds they manage, and determined how robust decisions were to decision makers' uncertainties and values.

Problem Statement

In SDM, the problem statement clearly and comprehensively defines the management issue and ensures that the right problem is being addressed (Gregory et al. 2012, Conroy and Peterson 2013, Runge et al. 2013). The problem statement establishes what, exactly, will be addressed with the decision-making process; misspecification of the issue results in solving the wrong problem. Crafting a good problem statement is challenging because multiple perspectives generally lead to divergent opinions about what the issue really is, even for close colleagues working on the same problem. Multiple iterations of the problem statement are often required because more may be learned about the problem at each step of the SDM process. Our working group refined the problem statement from Mitchell et al. (2013) to describe the issue of proactively managing pneumonia epizootics in bighorn sheep as:

> Montana Fish, Wildlife and Parks has direct experience with bighorn sheep pneumonia epizootic events that have affected conservation and public enjoyment of bighorn sheep. The agency currently has no tools for evaluating whether taking actions to proactively prevent similar events will produce more desirable results. 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

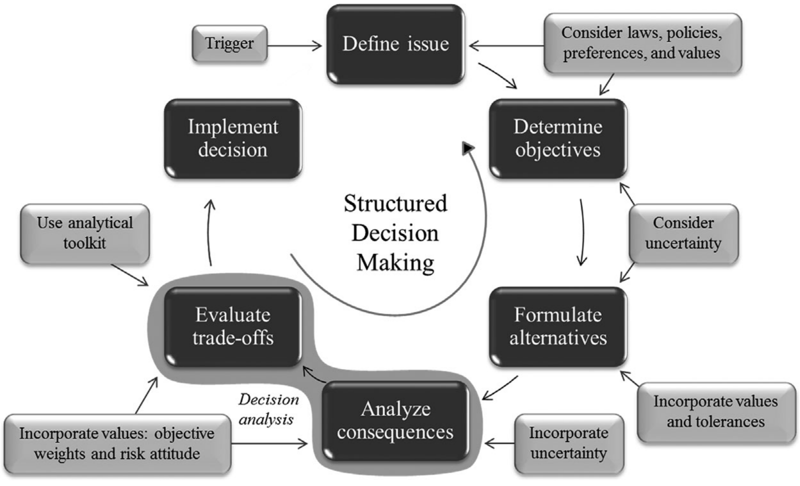

Figure 1. The structured decision making process (modified from Runge et al. (2013)), on which our decision tool for proactively managing pneumonia epizootics in bighorn sheep in Montana, USA is based. The trigger was the need for more proactive approaches to help prevent epizootics in Montana.

> bighorn sheep management and conservation remain local and community-based. Management actions and tools should be implemented with a monitoring program in a way that will reduce uncertainty and risk in the future.

Although the statement is straightforward and relatively simple, developing it was time-consuming, requiring iterated deliberations to distill the diversity of perspectives within the working group to a clear and concise consensus. The statement is arguably incomplete because it lacks elements generally considered important (i.e., a full description of who, what, when, where, why, and how that define and constrain a decision; Runge et al. 2013). Nonetheless, this statement presents what the group believed to be primary impediments to proactively managing pneumonia epizootics: the inability to predict pneumonia epizootics and to identify the most effective, efficient, and realistic approaches to managing them. It also describes important programmatic considerations: 1) flexibility is needed so that managers can decide on proactive management actions at the herd level, based on local operational, biological, and sociological conditions; and 2) any decision-making process needs to be adaptive, using monitoring to reduce uncertainty in risk estimation and efficacy of alternatives. Without the clarity of this problem statement, unexplored diversity of perspectives and values within the group (often assumed to be absent; Runge et al. 2013) would have impeded further progress toward developing an effective decision tool.

Fundamental Objectives

In SDM, fundamental objectives define what a fully successful solution to the management issue described in the problem statement would accomplish, and thus are the foundation for making good decisions (Gregory et al. 2012, Conroy and Peterson 2013, Runge et al. 2013). Fundamental objectives must be distinguished from means objectives that describe how successful solutions might be achieved (e.g., a fundamental objective of maximizing persistence of a threatened population compared to a means objective of increasing survival). Careful specification of the fundamental objectives is critical because they are used to evaluate trade-offs to determine how well management alternatives solve the problem. After specifying fundamental objectives, each is assigned a measure that allows the extent to which any management approach accomplishes the objective to be estimated realistically. As with the problem statement, specifying fundamental objectives is challenging because of divergent opinions about what should be accomplished. Iterated deliberations were required for our working group to arrive at a consensus on what successful proactive management of pneumonia epizootics in bighorn sheep should achieve. Ultimately, the group refined the fundamental objectives presented by Mitchell et al. (2013) as 6 objectives.

1. Maximize the probability of herd persistence (measured in terms of the decision maker's risk tolerance toward probability of a pneumonia epizootic).
2. Minimize operating costs (i.e., cost of day-to-day activities associated with management of bighorn sheep [measured in $US]).
3. Minimize personnel costs (i.e., cost of day-to-day activities associated with management activities [measured in days]).
4. Minimize crisis response costs (i.e., operating costs and costs of personnel time for responding to an epizootic [measured in $US]).
5. Maximize public satisfaction with viewing opportunity (measured as relatively low, medium, or high for the herd).
6. Maximize public satisfaction with hunting opportunity (measured in the predicted number of licenses issued).

Members of the working group determined that proactive management of pneumonia epizootics for any herd must strike a balance between maintaining viable numbers of bighorn sheep over time, minimizing budgetary and personnel costs, and maintaining satisfaction of the diverse publics interested in bighorn sheep. The likelihood of a decision accomplishing all considerations equally well is very small; realistically, any management approach will accomplish some fundamental objectives better than others, particularly where the objectives conflict (e.g., efforts needed to maximize the probability of persistence for a herd may be cost-prohibitive). The group chose measures for each fundamental objective based on information that would be available at the time decisions were made. Measures such as

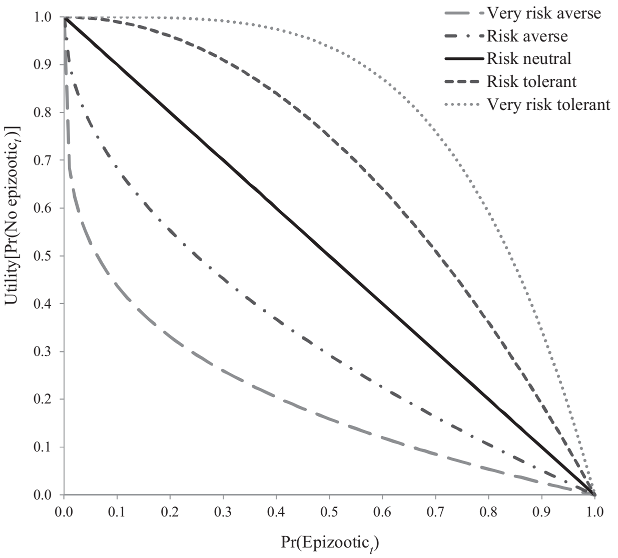

Figure 2. Risk attitude curves help incorporate risk tolerance in a formal decision-making process for how to proactively manage bighorn sheep to prevent pneumonia epizootics. After a decision maker selects a curve for tolerance towards risk of pneumonia epizootics for the herd, utility is calculated as $\text{Utility}[\Pr(\text{No epizootic}_t)]=1-\Pr(\text{Epizootic}_t)^r$, where $t=$ number of years over which risk is predicted and r is the risk tolerance factor (0.25, 0.5, 1, 2, or 4, corresponding to very risk averse, risk averse, risk neutral, risk tolerant, or very risk tolerant, respectively). These calculations are completed for each alternative for the fundamental objective of maximizing persistence.

dollars, person-days, and hunting licenses are straightforward (Runge et al. 2013). For maximizing viewing opportunity, where such measures are not yet available to decision makers, the group used a scale of low, medium, or high to represent expert opinion (Runge et al. 2013). An appropriate measure for maximizing the probability of herd persistence would at first glance seem straightforward (e.g., herd size, or probability of pneumonia), but these measures do not account for tolerance a decision maker might have for different levels of probabilities of herd persistence. We therefore developed a utility function representing the risk tolerance of a decision maker to the probability of pneumonia epizootics, based on the herd's risk of an epizootic estimated with the Sells et al. (2015) risk model. A utility function measures the value or desirability of an outcome to the decision maker (Edwards and Barron 1994). We calculated the utility as:

$$\mathrm{Utility}\left[\Pr\left(\text{No epizootic}_t\right)\right] = 1 - \Pr\left(\text{Epizootic}_t\right)^r$$

where t = number of years over which risk is predicted and r is the risk tolerance factor (0.25, 0.50, 1.00, 2.00, or 4.00, corresponding to very risk averse, risk averse, risk neutral, risk tolerant, or very risk tolerant, respectively; Fig. 2). As with the clarity achieved in the consensus problem statement, an unexplored diversity of perspectives among group members on what a good decision needed to achieve would have impeded development of an effective decision tool.

Alternatives

Alternatives are the potential management solutions designed to meet the fundamental objectives and solve the management issue (Gregory et al. 2012, Conroy and Peterson 2013, Runge et al. 2013). In practice, informal decision-making often begins with this step, without explicit consideration for the problem necessitating the decision or the objectives a good decision should accomplish (i.e., a decision is needed, what are my choices?; Runge et al. 2013), which can result in ineffective and wasteful decisions. Good alternatives thus proceed from an explicit, deliberative understanding of the full context for the decision. Alternatives may include a single action, or a set of multiple actions called portfolios. Each alternative must 1) address the future, not the past; 2) be unique; 3) be financially, legally, and politically reasonable; 4) be implementable by the decision maker; and 5) have implications for all fundamental objectives (Runge et al. 2013). Because no single alternative is likely to meet all fundamental objectives equally well, developing multiple alternatives reflecting different management strategies is important. Contrasting such alternatives through subsequent decision analysis provides important insights into the trade-offs inherent in making any decision.

For pneumonia in bighorn sheep, the biological uniqueness, estimated risk, decision timing, and management context of each herd meant that alternatives and optimal decisions would differ among herds, so our process was not designed to produce a one-size-fits-all decision. We designed our decision tool for application to individual herds by the biologists or program managers responsible for them (i.e., the decision makers for each herd) at times of their choosing. Whereas the problem statement and fundamental objectives were universal for herds managed by MFWP, the remaining steps of the SDM process were unique to each herd and required specific input from the decision maker responsible for the herd.

To help each decision maker develop a set of alternatives unique to his or her herd, the working group developed a table of potential actions that could be taken to reduce individual risk factors identified by Sells et al. (2015), ordered from least to most aggressive (Table 2). Any one or combination (i.e., a portfolio) of these actions, or others deemed appropriate by a herd's manager, could constitute unique alternatives. Decision makers designed alternatives to be implemented for t years, representing the timeframe of

Table 2. Example management actions based on techniques biologists and managers thought would successfully reduce risk from the risk factors identified by Sells et al. (2015) for pneumonia epizootics in bighorn sheep, Montana, USA. Decision makers can combine any set of these or other actions into a portfolio representing an alternative of interest for how to proactively manage a herd of bighorn sheep. Actions are ordered from least to most aggressive.

	Alternatives to address risk factors			
	Private land	**Weed control**	**Neighbor risk**	**Density**
Least aggressive actions	Do nothing	Do nothing	Do nothing	Do nothing
	Public education, grazing systems, livestock replacement	Public education	Manage for young ram season	Harvest ewes and young rams, ranging from a large number of licenses to unlimited
	Conservation easements, fee title purchases	Remove wandering bighorn	Create lethal removal zones around herd	Address range health by expanding, improving habitat
	Covenants, zoning	Create standards for fencing and herders	Cull herd	Trap, transplant, and relocate away from herd
	Remove or haze wandering bighorn	Change timing of grazing using domestic sheep and goats		Trap, transplant, and relocate within herd to expand range
Most aggressive actions	Remove wandering domestic sheep and goats	Replace domestic sheep and goats with biocontrols or herbicides		

their choice. Actions representing the current approach to managing epizootics for a herd are defined as the status quo alternative. Comparisons of new alternatives to the status quo provide key insights into how different management practices may or may not improve on current ones.

Decision Analysis

Multiple approaches to formal decision analysis exist in SDM to identify the optimal decision given the problem, fundamental objectives, and set of alternatives (Gregory et al. 2012, Conroy and Peterson 2013, Runge et al. 2013). Each approach includes predicting consequences of each alternative for each fundamental objective, evaluating trade-offs between alternatives for each fundamental objective, and identifying relative support for each alternative as an optimal solution to the management issue (von Winterfeldt and Edwards 1986, Edwards and Barron 1994, Gregory et al. 2012, Conroy and Peterson 2013, Runge et al. 2013). We based our decision analysis on the Simple Multi-Attribute Ranking Technique (SMART; Edwards and Barron 1994, Goodwin and Wright 2004). This approach clarifies trade-offs and overall support for each alternative by converting the estimated consequences to a common scale and incorporating the relative importance of each fundamental objective to the decision maker.

Predicting consequences.—Consequences are the estimated effects of each alternative on each fundamental objective; their prediction is required to evaluate the efficacy and trade-offs of each alternative and identify an optimal decision (Gregory et al. 2012, Conroy and Peterson 2013, Mitchell et al. 2013, Runge et al. 2013). Whether an epizootic ultimately occurs in a herd of bighorn sheep or not is an important source of uncertainty when evaluating alternatives for proactive management. The consequences of any decision are heavily dependent on the likelihood of an epizootic occurring; intensive actions may be wasted on a herd unlikely to experience an epizootic and insufficient actions may do little to preclude an epizootic in a herd at high risk. Additionally, each alternative will uniquely affect the likelihood of these outcomes. To make a good decision, decision makers must understand the probability of an epizootic for the herd in question and the effect of this probability when estimating consequences of management alternatives. We therefore incorporated the empirical model for predicting risk of an epizootic developed by Sells et al. (2015) into our decision analysis. Decision makers first estimated how actions in the portfolio would affect each risk factor, *R* (e.g., Table 3). We then inserted each *R* into the risk model to calculate logit risk and associated credibility intervals (CRIs; Table 1; Sells et al. 2015) and transformed logit risk to predicted probability of an epizootic in 1 year, $\Pr(\text{Epizootic}_1)$, for each alternative. From this equation, we calculated risk of ≥ 1 epizootic occurring in the next *t* years (i.e., the length of time the decision maker would implement the alternative) as:

$$\Pr(\text{Epizootic}_t) = 1 - [1 - \Pr(\text{Epizootic}_1)]^t$$

and probability of no epizootic as:

$$\Pr(\text{No epizootic}_t) = 1 - \Pr(\text{Epizootic}_t)$$

(Mood et al. 1974).

Table 3. Risk prediction table from our decision tool showing estimated probability of pneumonia epizootics, $\Pr(\text{Epizootic}_t)$, for alternatives evaluated for the Petty Creek herd of bighorn sheep, Montana, USA. Decision makers predicted how alternatives would affect each risk factor, *R*, identified by the Sells et al. (2015) risk model, which was then used to calculate 1- and 5-year $\Pr(\text{Epizootic}_t)$, where *t* was number of years. Although Sells et al. (2015) designed most risk factors as categorical, we treated all *R* as continuous with a 0–1 range because we expected few actions could realistically eliminate a risk factor entirely (i.e., completely reduce a categorical *R* from 1 [full effect] to 0 [no effect]). Instead, the decision maker estimated reductions in *R* (e.g., here, the decision maker thought that alternative 2 would make the effect of density a medium level with 0.60 value compared to alternative 1's estimated high density with 0.90 value). Risk factors of concern for Petty Creek were private land, neighbor risk, and density. Alternatives are described in the footnotes.

	***R* inputs (predicted impact on risk factors)**				**$\Pr(\text{Epizootic}_t)$**		**$\Pr(\text{Epizootic}_5)$ CRI[a]**	
Alternative	**Private land (%)[b]**	**Weed control**	**Neighbor risk**	**Density (L, M, or H)[c]**	**1-yr[d]**	**5-yr[e]**	**10% CRI**	**90% CRI**
1) Status quo[f]	50	0	0.15	H, 0.90	0.06	0.26	0.15	0.43
2) Transplant removal[g]	36	0	0.05	M, 0.60	0.01	0.04	0.02	0.07
3) Lethal removal[h]	43	0	0.10	M, 0.80	0.01	0.07	0.04	0.13
4) Easement[i]	45	0	0.15	H, 0.65	0.03	0.13	0.07	0.22

[a] 80% credibility intervals quantified uncertainty for $\Pr(\text{Epizootic}_5)$.

[b] The *R* input for the risk model requires percentage of private land to be standardized into units, calculated as (% - 25.58)/14.53, based on the mean percentage of private land (25.58%) and SD (14.53%) for herds in Montana.

[c] L = low, M = medium, H = high, based on herd-specific range in density from 1979–2013.

[d] Calculated using the *R* inputs and parameter values from the risk model.

[e] $\Pr(\text{Epizootic}_t) = 1 - [1 - \Pr(\text{Epizootic}_1)]^t$ for *t* years.

[f] The status quo alternative included reducing risk through public education about disease risk to bighorn sheep from domestic sheep and goats, maintaining separation through removing wandering domestic sheep or goats, aerial surveys to document population status, and harvest management to achieve density targets.

[g] The transplant removal alternative included reducing risk by removing bighorn sheep through a transplant operation to reduce density, plus public education about disease risk from domestic sheep and goats on private land, maintaining separation through removing or hazing wandering bighorn sheep along with removing wandering domestic sheep or goats, and aerial surveys and harvest management.

[h] The lethal removal alternative included lethal removal zones around the herd to reduce risk by maintaining separation from domestic sheep or goats, plus public education about disease risk from domestic sheep and goats on private land, aerial surveys, and harvest management.

[i] The easement alternative included conservation easements and fee title purchases to reduce risk from hobby farms with domestic sheep and goats, plus improvement of range health, public education about disease risk from domestic sheep and goats on private land, aerial surveys, and harvest management.

Next, the decision maker predicted consequences for each alternative's measurable effect on each fundamental objective in the event an epizootic did or did not occur over time interval t (e.g., Table 4). Decision makers used their expert opinion and local knowledge for each herd to estimate each consequence.

Finally, we transformed consequences to make them comparable across fundamental objectives (Table 4). We first calculated the expected value (EV) of each consequence for each fundamental objective to incorporate the likelihood of the consequence occurring and transform each pair of consequences into a single value:

$$\text{EV} = \text{Consequence}_{\text{Epizootic}} \times \Pr(\text{Epizootic}_t) + \text{Consequence}_{\text{No epizootic}} \times \Pr(\text{No epizootic}_t)$$

Table 4. Decision analysis results for managing risk of pneumonia epizootics for the Petty Creek herd of bighorn sheep, Montana, USA. The decision maker predicted consequences under each fundamental objective for each alternative, considering 2 potential outcomes (epizootic and no epizootic). Overall support indicated that both alternatives 2 and 3 were optimal decisions. Trade-offs in scores in the last part of the table were important to consider. Alternative 2 had the highest scores for persistence, crisis response costs, and viewing opportunity, with trade-offs of the worst hunting opportunity and the second-worst personnel costs. Alternative 3 trade-offs included lower scores for fundamental objectives scoring highest in alternative 2 but slightly better scores for personnel costs and hunting opportunity.

		Alternative			
Analysis	**Fundamental objective**	**1. Status quo**	**2. Transplant removal**	**3. Lethal removal**	**4. Easement**
Pr(Epizootic$_5$)[a]		0.26	0.04	0.07	0.13
Consequences if epizootic occurs					
	Maximize persistence (Utility, Pr(No epizootic$_5$))[b]	0.00	0.00	0.00	0.00
	Minimize operating costs ($US × 1,000, 5-yr)	37.50	75.00	75.00	787.50
	Minimize personnel costs (person-days, 5-yr)	70.00	180.00	125.00	370.00
	Minimize crisis response ($US × 1,000, 5-yr)	45.00	45.00	45.00	45.00
	Maximize viewing opportunity (1 = L, 2 = M, 3 = H)[c]	2.00	2.00	2.00	2.00
	Maximize hunting opportunity (no. licenses, 5-yr)	20.00	12.50	20.00	50.00
Pr(No epizootic$_5$)[d]		0.74	0.96	0.93	0.87
Consequences if no epizootic occurs					
	Maximize persistence (Utility, Pr(No epizootic$_5$))	0.28	0.56	0.48	0.40
	Minimize operating costs ($US × 1,000, 5-yr)	37.50	75.00	75.00	787.50
	Minimize personnel costs (person-days, 5-yr)	70.00	180.00	125.00	370.00
	Minimize crisis response ($US × 1,000, 5-yr)	0.00	0.00	0.00	0.00
	Maximize viewing opportunity (1 = L, 2 = M, 3 = H)	3.00	3.00	3.00	3.00
	Maximize hunting opportunity (no. licenses, 5-yr)	40.00	25.00	40.00	100.00
Expected values (EV)[e]					
	Maximize persistence	0.28	0.56	0.48	0.40
	Minimize operating costs	37.50	75.00	75.00	787.50
	Minimize personnel costs	70.00	180.00	125.00	370.00
	Minimize crisis response	11.87	1.73	3.26	5.75
	Maximize viewing opportunity	2.74	2.96	2.93	2.87
	Maximize hunting opportunity	34.73	24.52	38.55	93.61
Normalized values (EV′)[f]					
	Maximize persistence	0.00	1.00	0.72	0.43
	Minimize operating costs	1.00	0.95	0.95	0.00
	Minimize personnel costs	1.00	0.63	0.82	0.00
	Minimize crisis response	0.00	1.00	0.85	0.60
	Maximize viewing opportunity	0.00	1.00	0.85	0.60
	Maximize hunting opportunity	0.15	0.00	0.20	1.00
Scores[g]					
	Maximize persistence ($w_i = 0.21$)[h]	0.00	0.21	0.15	0.09
	Minimize operating costs ($w_i = 0.16$)	0.16	0.15	0.15	0.00
	Minimize personnel costs ($w_i = 0.17$)	0.17	0.11	0.14	0.00
	Minimize crisis response ($w_i = 0.13$)	0.00	0.13	0.11	0.08
	Maximize viewing opportunity ($w_i = 0.14$)	0.00	0.14	0.12	0.08
	Maximize hunting opportunity ($w_i = 0.19$)	0.03	0.00	0.04	0.19
Overall support[i]		0.36	0.74	0.71	0.44

[a] Pr(Epizootic$_5$) was calculated with the Sells et al. (2015) risk model.

[b] Consequences for persistence were based on the decision maker's risk attitude toward Pr(Epizootic$_5$).

[c] Low (L), medium (M), or high (H) viewing opportunity.

[d] Pr(No epizootic$_5$) = 1 − Pr(Epizootic$_5$).

[e] Expected values, EV = Consequence$_{\text{Epizootic}}$ × Pr(Epizootic$_5$) + Consequence$_{\text{No epizootic}}$ × Pr(No epizootic$_5$). We did not perform this calculation for herd persistence because its original form represented an EV.

[f] Normalized values, $\text{EV}' = (\text{EV} - \text{EV}_{min})/(\text{EV}_{max} - \text{EV}_{min})$ for EV within an objective if the goal was to maximize, $(\text{EV} - \text{EV}_{max})/(\text{EV}_{min} - \text{EV}_{max})$ if minimize.

[g] Scores = EV′ × w_i and clarified trade-offs in performance of each alternative for each fundamental objective.

[h] Weights, w_i, were based on swing weighting.

[i] Overall support = Σ(scores) in each column; higher support indicated more optimal decisions.

(Gregory et al. 2012). We did not perform this calculation for herd persistence because its original form represented an EV. We then normalized EVs to a 0–1 scale so that all consequences were directly comparable.

Evaluating trade-offs.—Trade-offs occur in SDM when no alternative performs best on all fundamental objectives; rarely do perfect alternatives exist, necessitating identifying the alternative that is most optimal (Gregory et al. 2012, Runge et al. 2013). Decision analysis incorporates a decision maker's values and priorities so they can evaluate trade-offs in the costs and benefits of alternatives. Although the 6 fundamental objectives we identified were universal for herds managed by MFWP, their relative importance differed for managing each herd. Decision makers therefore specified weights (w_i) of importance for each fundamental objective (i) using swing weighting to rank and score relative preferences in hypothetical swings in consequences from worst- to best-case scenario for each objective (Table 4; von Winterfeldt and Edwards 1986, Edwards and Barron 1994, Gregory et al. 2012, Runge et al. 2013). Resulting w_i captured the relative importance of meeting each fundamental objective for the herd in question.

We explicitly depicted trade-offs in relative performance of each alternative through scores, calculated as the product of each normalized consequence and weight of the associated fundamental objective (Table 4; von Winterfeldt and Edwards 1986, Edwards and Barron 1994, Gregory et al. 2012, Mitchell et al. 2013, Runge et al. 2013). Decision makers then evaluated trade-offs by comparing scores within each fundamental objective, where the alternatives with higher scores were predicted to meet that objective better than alternatives with lower scores.

Decision support.—Finally, we calculated overall decision support by summing each alternative's scores to help the decision maker identify an optimal decision to implement. Whereas individual scores made trade-offs explicit, overall support indicated the optimality of each decision. Alternatives with higher support would better meet the fundamental objectives based on predicted risk, consequences, and importance of each objective. It was possible, however, for an alternative with lower support to provide a better compromise by outperforming on certain fundamental objectives or by more evenly satisfying a wider range of objectives. Ultimately, the decision analysis clarified trade-offs and relative optimality of alternatives, but the decision maker made the final selection of alternative to implement (Gregory et al. 2012, Runge et al. 2013). A decision maker dissatisfied with the outcome could design and evaluate new alternatives based on what was learned from the analysis.

APPLICATIONS

Biologists and managers in our working group created and evaluated a set of alternatives specific to herds they managed. We selected 2 herds in northwestern Montana, Petty Creek and Bonner, as example applications for this paper. The Petty Creek herd west of Missoula, Montana had >125 individuals as of 2014 and was estimated to be at moderate-risk (Table 3). Given recent epizootics nearby, the decision maker for this herd was very risk averse toward an epizootic. Approximately 16 km east from the Petty Creek herd, separated by extensive topographical and anthropogenic obstacles, was the high-risk Bonner herd, which experienced a pneumonia epizootic in 2010. The decision maker for Bonner was very risk tolerant because of the recent epizootic, counts of only 11 animals in 2014, and a situation that seemed unlikely to improve in the near future without extensive, costly management. The decision makers developed unique alternatives for each herd, and evaluated which alternative was optimal for minimizing the estimated probability of an epizootic, given the unique biological, sociological, and management contexts for the herds.

The decision maker for Petty Creek developed 4 herd-specific alternatives (Table 3) and analyzed a 5-year timeframe for their implementation. Predicted $\Pr(\text{Epizootic}_5)$ for the alternatives ranged from 0.04–0.26 (Table 3). Alternative 2 focused on reducing density by removing part of the herd for transplant elsewhere and had greatest overall support at 0.74 (Table 4; Fig. 3); it had the highest scores for persistence, crisis response costs, and

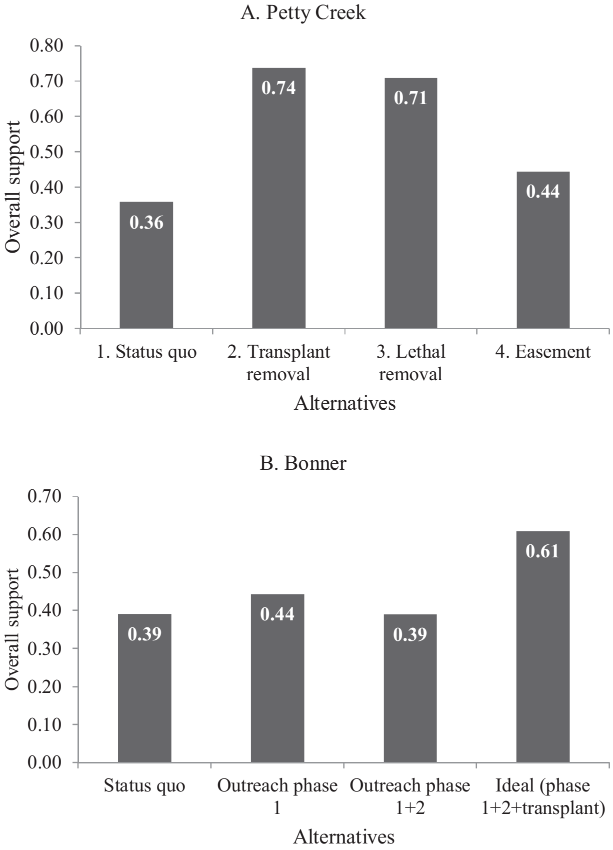

Figure 3. Overall support for alternatives (i.e., potential decisions) decision makers evaluated to proactively manage risk of pneumonia epizootics for the (A) Petty Creek and (B) Bonner herds of bighorn sheep in Montana, USA. Higher overall support, calculated based on the Simple Multi-Attribute Ranking Technique (SMART; Edwards and Barron 1994, Goodwin and Wright 2004), indicated more optimal decisions.

viewing opportunity but the worst hunting opportunity and second-worst personnel costs. Alternative 3 focused on lethal removal zones to reduce risk from neighboring herds and was nearly as optimal with 0.71 overall support; it included lower scores for fundamental objectives scoring highest in alternative 2 but slightly better scores for personnel costs and hunting opportunity. Analysis therefore suggested that either alternative would be an effective decision, depending on the degree to which the decision maker valued the gains and losses in relative performance in persistence, crisis response costs, and viewing opportunity versus personnel costs and hunting opportunity. Valuation of these trade-offs required the decision maker's consideration of subtle differences among alternatives that were clarified by the decision analysis. Alternative 3 arguably provided a better balance for meeting all fundamental objectives, whereas alternative 2 provided slight improvements on several objectives but at the cost of sharply decreased hunting opportunity.

The decision maker for Bonner developed 4 herd-specific alternatives with a 10-year timeframe and resulting Pr(Epizootic$_{10}$) ranging from 0.17–0.72 (Table 5). The most aggressive alternative, alternative 4, was optimal for Bonner with overall support of 0.61 (Table 6, Fig. 3), albeit with caveats. The alternative focused on intensive public education plus augmentation of the herd to boost numbers to avoid extirpation of the herd, and had the highest scores on all fundamental objectives except operating and personnel costs. Remaining alternatives focusing on the status quo or intensive public education were not comparable with support of $\leq$0.44. If, however, the decision maker decided to eliminate alternative 4 from consideration (e.g., if pathogen levels were deemed too high for herd augmentation; Plowright et al. 2013), the results of the decision analysis changed. In this case, the 3 remaining alternatives would all perform nearly equally with overall support of 0.39–0.44, with no clearly preferred decision. The optimal decision would then likely be the status quo, for investment of further effort would unlikely improve the decision maker's ability to meet the fundamental objectives. Had the status quo been unacceptable to the decision maker, development and evaluation of new alternatives based on what was learned in the first iteration of SDM had the potential to produce a more satisfactory solution.

The focus of our decision tool on herd-level management did not preclude consideration of management effects across multiple herds; managers using our tool were required to consider explicitly how neighboring herds might affect probability of a pneumonia epizootic for a focal herd. For example, the decision makers for the Petty Creek and Bonner herds, above, had to consider the potential for infected bighorn sheep from either herd traveling the 16 km separating them (Tables 3 and 5). The optimal management alternatives for both herds thus included actions (hazing and removal) to prevent contact from bighorn sheep wandering between them. Thus, optimal strategies for each herd are interrelated. Although the decision tool does not explicitly consider how management actions in a particular herd affect neighboring herds, the interdependency of herd-level decisions across spatially proximate herds allows implicit evaluation of multi-herd management strategies. Should the likelihood of an epizootic for either herd change (as a product of management or not), another iteration of our decision analysis may support different optimal management approaches for either herd. An explicit evaluation of multi-herd management would require decision makers to formally evaluate consequences of herd-level management on neighboring herds in a linked decision-making process.

Table 5. Risk prediction table from our decision tool showing estimated probability of pneumonia epizootics, Pr(Epizootic$_t$), for alternatives evaluated for the Bonner herd of bighorn sheep, Montana, USA. Decision makers predicted how alternatives would affect the risk factors identified by the Sells et al. (2015) risk model, which was then used to calculate 1- and 10-year Pr(Epizootic$_t$), where t was number of years. Alternatives are described in the footnotes.

	***R* inputs (predicted impact on risk factors)**				**Pr(Epizootic$_t$)**		**Pr(Epizootic$_{10}$) CRI**[a]	
Alternative	**Private land (%)**[b]	**Weed control**	**Neighbor risk**	**Density (L, M, or H)**[c]	**1-yr**[d]	**10-yr**[e]	**10% CRI**	**90% CRI**
1. Status quo[f]	50	1	1	L, 1.00	0.12	0.72	0.36	0.95
2. Outreach phase 1[g]	45	0	1	L, 1.00	0.03	0.29	0.11	0.58
3. Outreach phase 1 + 2[h]	30	0	1	L, 1.00	0.02	0.20	0.08	0.40
4. Ideal (1 + 2 + transplant)[i]	25	0	1	L, 1.00	0.02	0.17	0.07	0.35

[a] 80% credibility intervals quantified uncertainty for Pr(Epizootic$_{10}$).

[b] The *R* input for the risk model requires percentage of private land to be standardized into units, calculated as (% - 25.58)/14.53, based on the mean percentage of private land (25.58%) and SD (14.53%) for herds in Montana.

[c] L = low, M = medium, H = high, based on herd-specific range in density from 1979–2013.

[d] Calculated using the *R* inputs and parameter values from the risk model.

[e] $\Pr(\text{Epizootic}_t) = 1 - [1 - \Pr(\text{Epizootic}_1)]^t$ for t years.

[f] The status quo alternative included aerial surveys to document population status, post-epizootic monitoring and necropsies, and reducing risk through public education about disease risk to bighorn sheep from domestic sheep and goats, maintaining separation by removing wandering domestic or bighorn sheep if found comingling, and maintaining separation using fencing and herders by the City of Missoula for domestic sheep weed control operations.

[g] The outreach phase 1 alternative included all status quo actions plus increased outreach, with focus on more public education about disease risk to bighorn sheep from domestic sheep and goats and working with the City of Missoula to end weed control with domestic sheep.

[h] The outreach phase 1 + 2 alternative included all outreach phase 1 actions plus additional public outreach and coordination to obtain public buy-in to work as a community to keep domestic sheep and goats separate from bighorn sheep.

[i] The ideal alternative included all outreach phase 1 + 2 actions plus an augmentation to increase herd size.

Table 6. Decision analysis results for managing risk of pneumonia epizootics for the Bonner herd of bighorn sheep, Montana, USA. The decision maker predicted consequences under each fundamental objective for each alternative, considering 2 potential outcomes (epizootic and no epizootic). Overall support indicated that Alternative 4 was the optimal decision, performing best on all fundamental objectives except operating and personnel costs. Remaining alternatives had low overall support and would not provide worthwhile trade-offs in scores.

		Alternative			
Analysis	**Fundamental objective**	**1. Status quo**	**2. Outreach phase 1**	**3. Outreach phase 1 + 2**	**4. Ideal (1 + 2 + transplant)**
Pr(Epizootic$_{10}$)[a]		0.72	0.29	0.20	0.17
Consequences if epizootic occurs					
	Maximize persistence (Utility, Pr(No epizootic$_{10}$))[b]	0.00	0.00	0.00	0.00
	Minimize operating costs ($US × 1,000, 10-yr)	100.00	200.00	220.00	241.00
	Minimize personnel costs (person-days, 10-yr)	210.00	550.00	650.00	692.00
	Minimize crisis response ($US × 1,000, 10-yr)	18.00	18.00	18.00	18.00
	Maximize viewing opportunity (1 = L, 2 = M, 3 = H)[c]	1.00	1.00	1.00	1.00
	Maximize hunting opportunity (no. licenses, 10-yr)	0.00	0.00	0.00	5.00
Pr(No epizootic$_{10}$)[d]		0.28	0.71	0.80	0.83
Consequences if no epizootic occurs					
	Maximize persistence (Utility, Pr(No epizootic$_{10}$))	0.73	0.99	1.00	1.00
	Minimize operating costs ($US × 1,000, 10-yr)	100.00	200.00	220.00	241.00
	Minimize personnel costs (person-days, 10-yr)	210.00	550.00	650.00	692.00
	Minimize crisis response ($US × 1,000, 10-yr)	0.00	0.00	0.00	0.00
	Maximize viewing opportunity (1 = L, 2 = M, 3 = H)	2.00	2.00	2.00	3.00
	Maximize hunting opportunity (no. licenses, 10-yr)	0.00	0.00	0.00	10.00
Expected values (EV)[e]					
	Maximize persistence	0.73	0.99	1.00	1.00
	Minimize operating costs	100.00	200.00	220.00	241.00
	Minimize personnel costs	210.00	550.00	650.00	692.00
	Minimize crisis response	12.94	5.21	3.55	3.11
	Maximize viewing opportunity	1.28	1.71	1.80	2.65
	Maximize hunting opportunity	0.00	0.00	0.00	9.14
Normalized values (EV′)[f]					
	Maximize persistence	0.00	0.98	1.00	1.00
	Minimize operating costs	1.00	0.29	0.15	0.00
	Minimize personnel costs	1.00	0.29	0.09	0.00
	Minimize crisis response	0.00	0.79	0.96	1.00
	Maximize viewing opportunity	0.00	0.31	0.38	1.00
	Maximize hunting opportunity	0.00	0.00	0.00	1.00
Scores[g]					
	Maximize persistence ($w_i = 0.29$)[h]	0.00	0.28	0.29	0.29
	Minimize operating costs ($w_i = 0.19$)	0.19	0.05	0.03	0.00
	Minimize personnel costs ($w_i = 0.20$)	0.20	0.06	0.02	0.00
	Minimize crisis response ($w_i = 0.00$)	0.00	0.00	0.00	0.00
	Maximize viewing opportunity ($w_i = 0.14$)	0.00	0.05	0.06	0.14
	Maximize hunting opportunity ($w_i = 0.17$)	0.00	0.00	0.00	0.17
Overall support[i]		0.39	0.44	0.39	0.61

[a] Pr(Epizootic$_{10}$) was calculated with the Sells et al. (2015) risk model.

[b] Consequences for persistence were based on the decision maker's risk attitude toward Pr(Epizootic$_{10}$).

[c] Low (L), medium (M), or high (H) viewing opportunity.

[d] Pr(No epizootic$_{10}$) = 1 − Pr(Epizootic$_{10}$).

[e] Expected values, $\text{EV} = \text{Consequence}_{\text{Epizootic}} \times \Pr(\text{Epizootic}_{10}) + \text{Consequence}_{\text{No epizootic}} \times \Pr(\text{No epizootic}_{10})$. We did not perform this calculation for herd persistence because its original form represented an EV.

[f] Normalized values, $\text{EV}' = (\text{EV} - \text{EV}_{min})/(\text{EV}_{max} - \text{EV}_{min})$ for EV within an objective if the goal was to maximize, $(\text{EV} - \text{EV}_{max})/(\text{EV}_{min} - \text{EV}_{max})$ if minimize.

[g] Scores = EV′ × w_i and clarified trade-offs in performance of each alternative for each fundamental objective.

[h] Weights, w_i, were based on swing weighting.

[i] Overall support = Σ(scores) in each column; higher support indicated more optimal decisions. Values do not sum because of rounding.

Our decision model presently does not explicitly link herd-level decisions but could provide the foundation for such a decision analysis should managers see the need.

Robustness of Optimal Decisions

Having identified optimal decisions for each example herd, we next determined whether uncertainty in estimated risk of pneumonia or the value-based judgements of the decision maker had singly influenced the outcome. Uncertainty in estimated risk of pneumonia is captured by the CRIs from the risk model, whereas value-based judgements include risk attitude and weights on fundamental objectives. We therefore analyzed sensitivity to uncertainty in risk predictions, risk attitude, and weights on fundamental objectives by repeating the decision analysis using the range of potential inputs for each component and assessing if the optimal decision would change for either herd (von Winterfeldt and Edwards 1986, Conroy and Peterson 2013, Runge et al. 2013).

Our decision analyses were robust to uncertainty in Pr(Epizootic$_t$) based on the CRIs (Tables 3 and 5; Kéry 2010). Overall support for alternatives for both herds changed little when we replaced Pr(Epizootic$_t$) with lower (10%) or upper (90%) CRIs in turn in the decision analysis.

The optimal decisions were also robust to risk attitude, which we tested by repeating the decision analyses under each risk attitude in turn. Overall support of alternatives for Petty Creek fluctuated slightly at different risk attitudes but remained nearly identical. Alternative 4 remained optimal for Bonner, with minimal change in performance of other alternatives.

The optimal decisions were robust to weights on fundamental objectives (w_i), which we analyzed by varying a w_i from 0–1 while holding other w_i at their original values to identify the weights at which the optimal decision changed (von Winterfeldt and Edwards 1986). For Petty Creek, alternatives 2 and 3 nearly always retained the highest overall support regardless of w_i (Fig. 4), meaning changes in w_i would not result in a different, clearly superior decision. For Bonner, alternative 4 remained optimal unless the decision maker lowered the weight of herd persistence to a quarter of its original importance, in which case the status quo was optimal (Fig. 5). Alternative 1 was also optimal if the importance of either operating costs or personnel costs more than doubled; none of these changes in weights were feasible for the decision maker.

The various and numerous uncertainties and value-based judgements involved in decision-making are a critical reason why identifying optimal decisions is a complicated challenge. Explicit evaluation of these uncertainties and values helped make decisions transparent and defensible. Our sensitivity analyses showed the decision makers for Petty Creek and Bonner that no single uncertainty or value we tested would drive the optimal decisions for proactively managing pneumonia epizootics in either herd. Were a decision maker uncertain about other inputs, such as predicted consequences

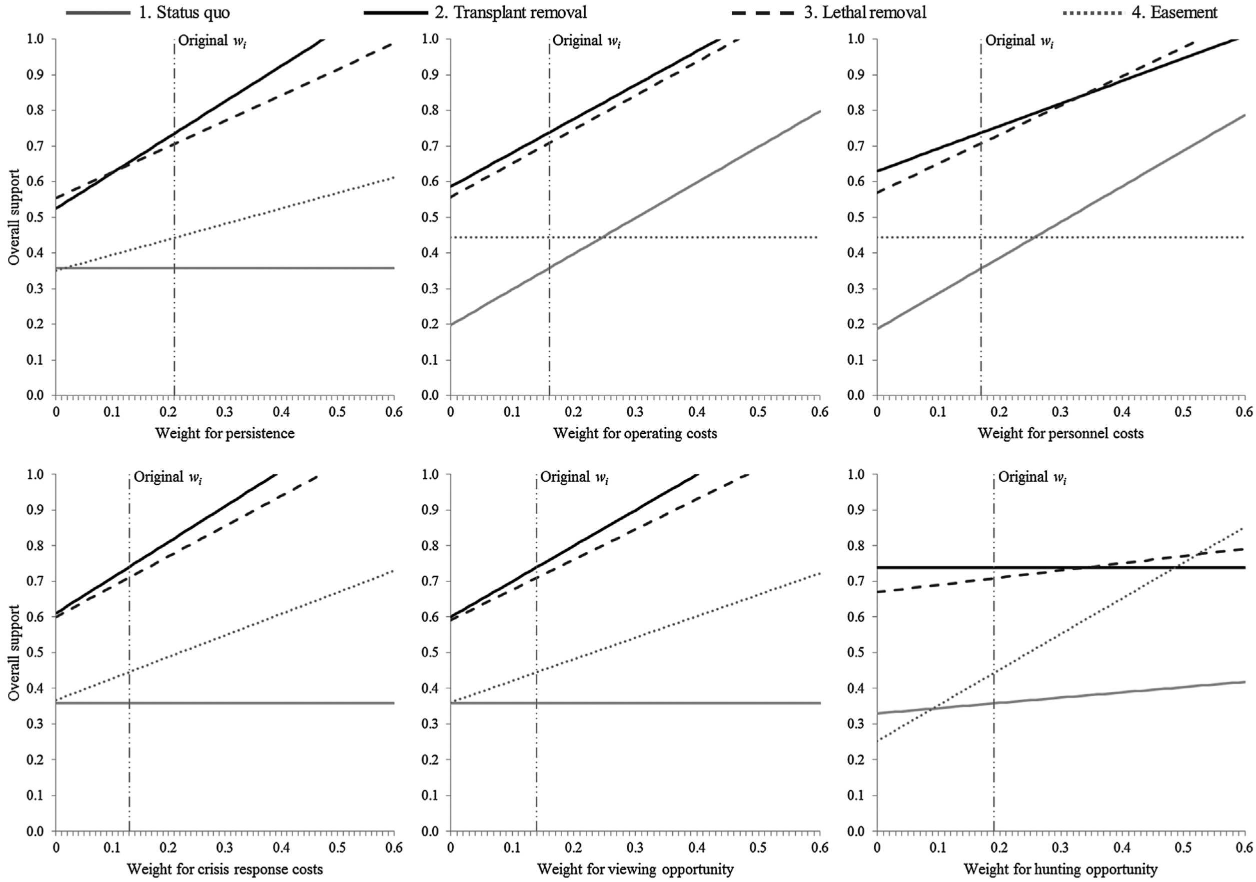

Figure 4. Optimal decisions had minimal sensitivity to weight on fundamental objectives, w_i, for managing risk of pneumonia epizootics in the Petty Creek herd of bighorn sheep in Montana, USA. We varied w_i for the named objective from 0–1 while holding w_i for the other objectives at original values. Lines correspond to the alternatives we evaluated, with higher overall support indicating more optimal decisions; the optimal decision changed where lines cross. Alternatives 2 and 3 nearly always retained the highest overall support regardless of w_i. The optimal decision changed from alternatives 2–3 if $w_{\text{persistence}} \leq 0.10$ (0.48 times the original $w_{\text{persistence}}$) or $w_{\text{personnel costs}} \geq 0.34$ (2.00 times the original $w_{\text{personnel costs}}$). The optimal decision also changed to alternative 3 at $w_{\text{hunting opportunity}} \geq 0.34$ (1.79 times the original $w_{\text{hunting opportunity}}$) and to alternative 4 at $w_{\text{hunting opportunity}} \geq 0.53$ (2.79 times the original $w_{\text{hunting opportunity}}$). None of these weights were deemed reasonable by the decision maker.

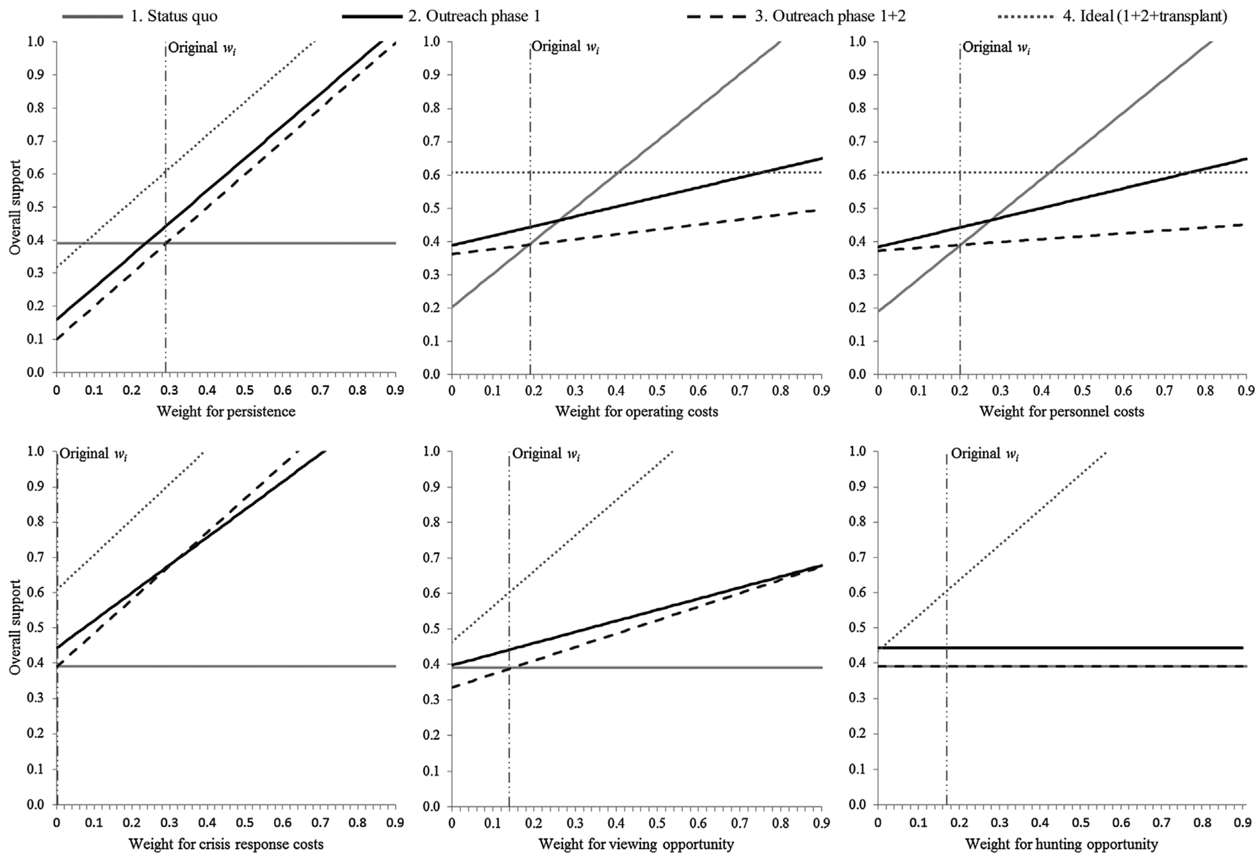

Figure 5. Optimal decisions had minimal sensitivity to weight on fundamental objectives, w_i, for managing risk of pneumonia epizootics in the Bonner herd of bighorn sheep in Montana, USA. We varied w_i for the named objective from 0−1 while holding w_i for the other objectives at original values. Lines correspond to the alternatives we evaluated, with higher overall support indicating more optimal decisions; the optimal decision changes where lines cross. The optimal decision changed from alternatives 4–1 only if $w_{\text{persistence}} \leq 0.07$ (0.24 times the original $w_{\text{persistence}}$), $w_{\text{operating costs}} \geq 0.41$ (2.16 times the original $w_{\text{operating costs}}$), or $w_{\text{opersonnel costs}} \geq 0.43$ (2.15 times the original $w_{\text{opersonnel costs}}$). None of these weights were deemed reasonable by the decision maker.

or effects of alternatives on risk, additional sensitivity analyses could test the influence of that uncertainty. In general, any single input is unlikely to solely influence an optimal decision because of the synergistic influences of the many inputs (von Winterfeldt and Edwards 1986). Had a decision been sensitive to an input, the decision maker could determine how to reduce associated uncertainty if necessary (e.g., by soliciting further expert opinion, or incorporating estimates from multiple experts). If this were not possible, the decision maker could acknowledge the uncertainty and move forward with the decision. Otherwise, making no decision is in fact a decision for the status quo.

MANAGEMENT IMPLICATIONS

Structured decision making can formally integrate biological knowledge, uncertainty, expert opinion, and values of decision makers to produce effective decisions for complex, multi-objective problems in wildlife management, where an informal decision-making process is unlikely to do so. Our decision tool based on SDM has been implemented by MFWP for managing herds because 1) its generality provides a consistent and explicit framework for managing all herds of bighorn sheep in Montana, and 2) its herd-specific nature provides flexibility for considering the uniqueness, estimated risk, decision timing, and management context of each herd, thereby avoiding a nonexistent one-size-fits-all decision. Use of our tool identified management actions most likely to prevent pneumonia epizootics for 2 herds of bighorn sheep in Montana, based on all information available about their unique biological, social, and management contexts. These decisions were transparent, providing clear justifications for selected management actions, and therefore defensible within MFWP, to stakeholders, and to the public. The consistent decision-making process across herds in Montana further facilitated communication within MFWP, with stakeholders, and with the public in explaining decisions using the same process and terminology for different herds. An upfront investment with a formal decision-making process thus allowed MFWP to pursue proactive measures to minimize risks of pneumonia epizootics when they were logical and well-supported based on a more clearly defined decision context, rather than being limited to reactive measures following pneumonia epizootics.

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