Recommendations for Managing Mountain Goats in Montana: A Decision Analysis Approach

Justin Gude, Nick DeCesare, Kelly Proffitt, Sarah Sells, Robert Garrott, Imtiaz Rangwala, Quentin Kujala, Mark Biel, Jessy Coltrane, Julie Cunningham, Tammy Fletcher, Julie Golla, Karen Loveless, Rebecca Mowry, Jesse Newby, Megan O'Reilly, Ryan Rauscher, Kevin Rose, Michael Thompson, and John Vore

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Abstract

We used a Structured Decision Making process to consider and recommend management guidelines and priority information needs for mountain goats in Montana. We identified several overarching objectives to be addressed in any management alternative, including: fostering cooperative working relationships among jurisdictions, mitigating impacts of human development or recreation on mountain goat distribution, combating habituation, managing conifer encroachment where possible, providing sustainable public opportunity to hunt and view mountain goats, and building public support for mountain goat conservation at local and larger scales. In addition to these essential mountain goat management components, we defined fundamental objectives of mountain goat management in Montana as the following.

1. Maximize the number of occupied mountain goat population units.
2. Maximize the number of mountain goat population units meeting population trend objectives statewide, considering limitations in each population unit.
3. Minimize disease risks to bighorn sheep.
4. Minimize disease risks to mountain goats.
5. Minimize cost.
6. Minimize social conflict resulting from mountain goat management.

We evaluated the efficacy of 7 alternative management strategies towards achieving these fundamental objectives.

1. Status Quo
2. Top-down mortality management
3. Introduction
4. Augmentation
5. Habitat protection
6. Combined, with augmentations
7. Combined, without augmentations

To make our evaluation, we developed quantitative predictions of the consequences of each alternative management strategy relative to each fundamental objective. We built a mountain goat habitat model to forecast the amount of occupied habitat under each alternative while accounting for uncertainty in the effects of climate change. We developed a population projection model to predict mountain goat population trend under each alternative while accounting for uncertainty in population demographics and dynamics. We predicted the disease risk posed by each alternative while accounting for uncertainty in the presence of pneumonia pathogens in extant populations of bighorn sheep and mountain goats and risk tolerance for mixing herds during translocations. We predicted costs and social conflicts using current budgets and professional judgement. Using these predictions in a decision analysis, we

arrived at general recommendations for mountain goat management and priority information needs in Montana.

First, we recommend that new population introductions of mountain goats be pursued as a strategy resilient to climate change. Continuing to strictly limit hunter harvest and focus harvest on adult male mountain goats in small populations will help increase the number of populations meeting trend objectives. Area closures of important mountain goat habitats should be considered only in areas where impacts to goat populations are relatively clear. Efforts to reduce carnivore densities in mountain goat herd ranges and mountain goat augmentations should only be implemented in a research and learning context. Such research will reduce uncertainties about the role of carnivores on mountain goat population dynamics and the effects of augmentations on respiratory disease epizootics in bighorn sheep and mountain goat populations. We determined that more information related to population dynamics and disease risks in mountain goats would directly affect the optimal choice among management strategies and improve the achievement of fundamental objectives. These 2 related uncertainties could be reduced through adaptive management, in which research and monitoring programs are implemented in concert with management actions in a way that decreases these uncertainties and improves the achievement of fundamental objectives.

Acknowledgements

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Background

Concerns about the current and future status of mountain goat populations have increased in recent years. Smith (2014) synthesized the behavior, status and ecology of mountain goats in North America and admonished that threats caused directly (e.g., hunting harvest or displacement) or indirectly (e.g., through climate change) by humans may reduce or extirpate populations. White et al. (2018) used demographic and habitat selection data from Alaska to project large-scale range declines and extirpation of mountain goat populations due to climate change. Lowrey et al. (2018a) documented a broad distribution among mountain goat populations of the respiratory pathogen complex associated with devastating pneumonia epizootics in bighorn sheep populations. These findings highlight a range of potential threats to mountain goat populations and the need to proactively develop strategies to mitigate these threats.

Montana Fish, Wildlife and Parks (FWP) has implemented mountain goat harvest management changes because of these increasing concerns, in combination with the limited, available monitoring data indicating that populations in western Montana are struggling. Since the 1960s, FWP has reduced hunting opportunity within the native range of mountain goats across western Montana by approximately 90%. This trend continued into the 2019 hunting season, when mountain goat hunting opportunity was largely eliminated across the Bob Marshall Wilderness Complex and when it became unlawful for hunters to harvest a female mountain goat in a group that contains one or more kids across most native ranges. Over the same period, harvest management and hunting opportunity in herds introduced by FWP across central and southwestern Montana have remained generally stable.

Smith and DeCesare (2017) summarized the last 50+ years of Montana mountain goat population data and management and highlighted the dichotomy between trends in native and introduced populations. Montana has 58 extant mountain goat herds including both native herds and herds introduced outside of their native range (Figure 1). Mountain goat abundance within their native range in Montana is approximately 25% of that estimated during the 1940s. Mountain goat herds introduced by FWP outside of their native range beginning in the 1940s are largely prospering, with some notable exceptions. Smith and DeCesare (2017) also emphasized the extremely limited amount of information available to inform management decisions for mountain goats. Smith and DeCesare (2017) highlighted many information needs, such as more reliable monitoring data, information on mountain goat habitat requirements and habitat quality, and basic, comparative demographic and population dynamics information among herds. However, so little is known about mountain goats that prioritizing information needs has proven difficult. Essentially any study of mountain goats employing modern wildlife

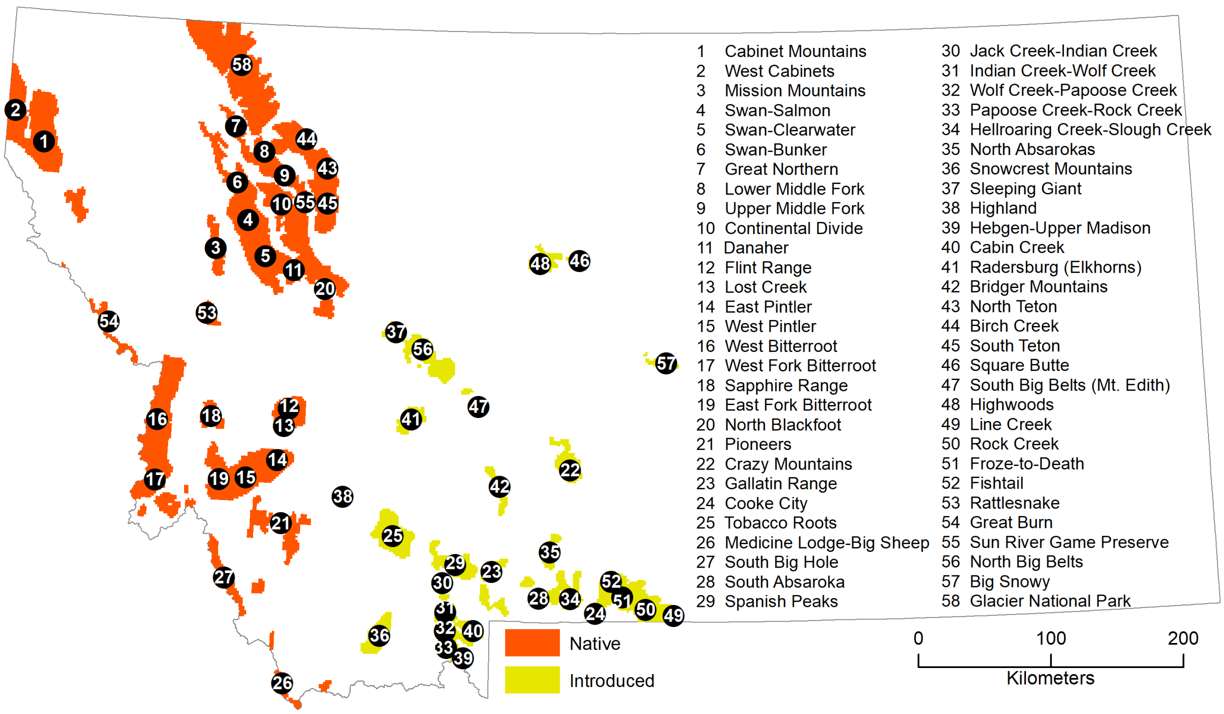

Figure 1. Current mountain goat distribution in Montana, divided into 58 population units existing within native ranges (orange) and introduced outside of native ranges (yellow).

research or survey methods would generate more information than is currently available, but whether and how any of this new information would inform management is unclear.

The objectives for mountain goat management in Montana have not been clearly defined, complicating efforts to identify priority information needs and assess the relative success of mountain goat conservation efforts. Biologists and managers can implement only a limited number of actions to manage mountain goats, and these actions have all been employed for decades in different herds across Montana. Whether past, recent or possible future management actions would help meet objectives in struggling or thriving populations is unclear. Also unclear is the relative degree to which different kinds of new information would help decide among or increase efficacy of actions to improve mountain goat management and conservation. If certain types of information would be more directly relevant to management decisions or would improve management, those types of information could be prioritized.

During 2018-19, FWP convened and facilitated a working group through a Structured Decision Making (SDM) process. The purpose of the SDM process was to provide overall management direction for mountain goats in Montana and articulate a portfolio of high priority monitoring and research needs tied directly to mountain goat management. SDM is a value-focused formalization of common sense, designed to ensure that all components of a decision are thoroughly considered in complex situations (Keeney 1982). SDM is an iterative process that breaks decision-making into its logical, component parts (Figure 2). This report summarizes the activities and products of this SDM process and is organized according to its component parts.

Working group composition and process

The working group consisted of professional biological staff from each FWP Region inhabited by mountain goats, as well as staff from the National Park Service and the United States Forest Service (USFS) Northern Region. Staff from the Confederated Salish and Kootenai Tribal Wildlife Program accepted an invitation to serve on the working group and were kept apprised of progress and products, but they were unable to attend any of the meetings. The following individuals therefore constituted the working group.

1. Mark Biel, Glacier National Park Natural Resources Program Manager
2. Tammy Fletcher, USFS Northern Region Wildlife Program Manager
3. Jessy Coltrane, FWP Region 1 Wildlife Biologist
    a. Substituted by Jesse Newby, FWP Region 1 Wildlife Research Technician, for one meeting.
4. Rebecca Mowry, FWP Region 2 Wildlife Biologist
    a. Substituted by Julie Golla, FWP Region 2 Wildlife Biologist, for one meeting.
5. Karen Loveless, FWP Region 3 Wildlife Biologist
    a. Replaced by Julie Cunningham, FWP Region 3 Wildlife Biologist, for the final two meetings after resigning from FWP.
6. Ryan Rauscher, FWP Region 4 Wildlife Biologist
7. Megan O'Reilly, FWP Region 5 Wildlife Biologist
    a. Substituted by Kevin Rose, FWP Region 5 Wildlife Program Manager, for one meeting.
8. John Vore, FWP Game Management Bureau Chief

FWP Region 2 Wildlife Program Manager Mike Thompson also attended and participated in 2 of the working group meetings. In addition to the working group membership, the process was supported by a science team focused on providing information and input throughout the SDM process, helping to devise performance measures for fundamental objectives, and predicting consequences of management actions.

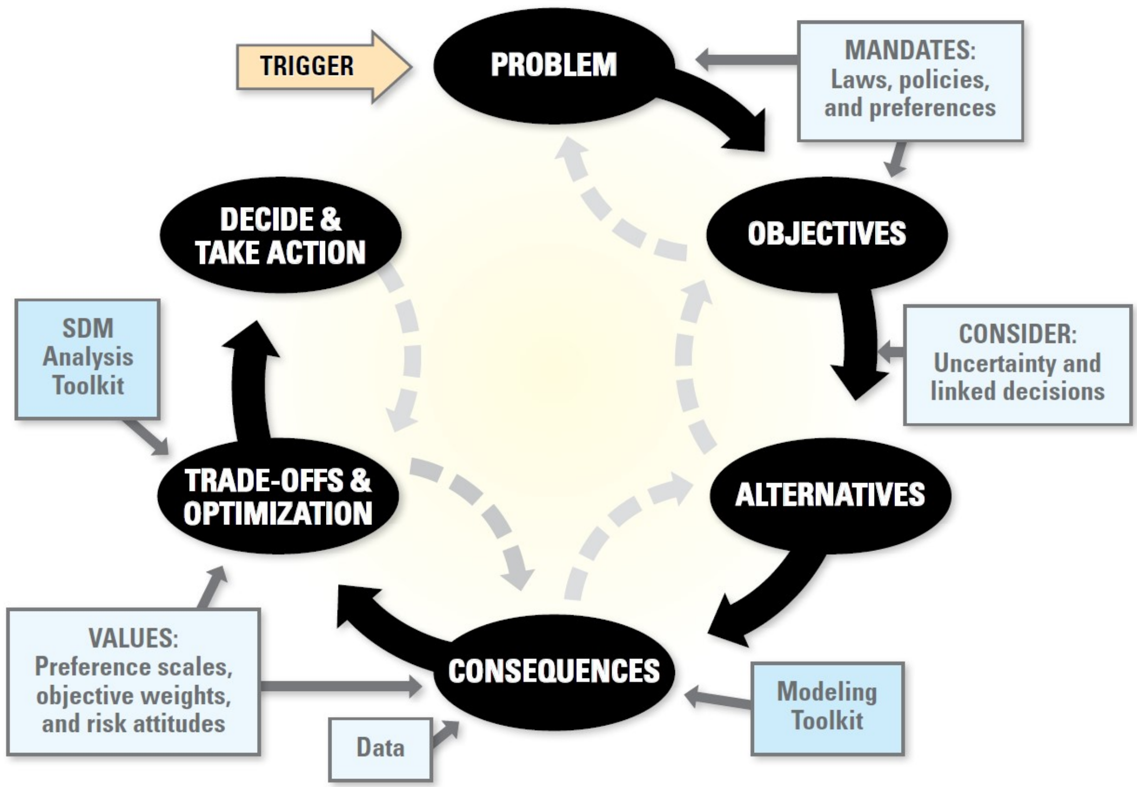

Figure 2. A schematic representation of the Structured Decision Making (SDM) process. The first three components involve articulation of the scope of the problem, objectives that comprehensively define what management should accomplish, and a portfolio of possible management alternatives. The subsequent steps include predicting consequences of alternative management actions, decision analysis to analyze trade-offs, and optimization to identify the set of management actions that are predicted to best achieve fundamental objectives. Decision analysis tools also permit identification of research or monitoring priorities that will impact the achievement of fundamental objectives and ultimately the decision about which management actions to take. Graphic is courtesy of the US Fish and Wildlife Service.

The science team consisted of the following individuals.

1. Nick DeCesare, FWP Research Wildlife Biologist
2. Kelly Proffitt, FWP Research Wildlife Biologist
3. Bob Garrott, Professor in the Ecology Department and Director of the Fish and Wildlife Management Program, Montana State University
4. Imtiaz Rangwala, Research Scientist at the North Central Climate Adaptation Science Center and the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder

The working group was facilitated through the SDM Process by Justin Gude (FWP Wildlife Research and Technical Services Bureau Chief), Quentin Kujala (FWP Wildlife Bureau

Coordinator), and Sarah Sells (PhD Candidate, University of Montana). Logistical support was provided by Karen Speeg and Kammi McClain, FWP Wildlife Division Administrative Support Supervisors. The working group met for 4, 2-day sessions followed by a 1-day video conference during May 2018- December 2019 to work through the SDM process. Additionally, the first 2-day session consisted of the following presentations by working group members and invited scientists and managers.

1. Idaho mountain goat status, management, and research (Mark Hurley, Idaho Department of Fish and Game)
2. Alaska mountain goat status, management, and research (Kevin White, Alaska Department of Fish and Game)
3. Alberta mountain goat status, management, and research (Kirby Smith, retired from Alberta Environment and Parks)
4. Glacier National Park mountain goat ecological science overview and National Park Service management and conservation program summary with an emphasis on native/ non-native approaches (Mark Biel, National Park Service)
5. US Forest Service summary of status, forest plan references, prospects for habitat management, and consideration of vegetation impacts by native and non-native mountain goat herds (Tammy Fletcher, US Forest Service Northern Region)
6. Yellowstone area mountain goat ecological science overview and summary of recent pathogen testing results (Bob Garrott, Montana State University)
7. Summary of climate history in alpine environments in Montana, alpine/ mountain climate science "101," and available climate data (Imtiaz Rangwala and Candida Dewes, Cooperative Institute for Research in Environmental Sciences)
8. Montana mountain goat information summary and status (Bruce Smith, retired from the US Fish and Wildlife Service)

Issue (Problem) Statement

FWP is charged with the stewardship of Montana's wildlife that contribute to the quality of life for present and future generations. Mountain goats, an ecologically important and iconic species, have declined across much of their range in Montana, raising concerns for their present and future status and impacting both consumptive and non-consumptive recreational opportunities. Management of mountain goats is hampered by multiple sources of uncertainty including a lack of information on abundance, vital rates, population boundaries, population impacts of ecological processes and predation, changing climatic conditions, and effects of shared respiratory pathogens with bighorn sheep. FWP requires a better understanding of these uncertainties to effectively manage mountain goats. Additional challenges to mountain goat management include a lack of funding, competition for limited agency resources for research and monitoring, logistics of working in remote, high elevation areas, limited public advocacy, and the absence of a management plan to provide guidance for addressing these uncertainties and management challenges. *By the end of 2019, the working group, collaborating with partners across various jurisdictions, will recommend guidelines to the FWP Wildlife Division Administrator and Director to include a suite of management strategies, identifying information gaps, and prioritizing monitoring and research needs to address mountain goat conservation challenges.* [Italics added to emphasize the expected products from the working group.]

Objectives

Overarching objectives

Overarching objectives need to be accomplished no matter the statewide management direction for mountain goats. They are an implied part of every management alternative the working group considered, and strategies to achieve the overarching objectives should be pursued. Because the overarching objectives are to be addressed in every management alternative the working group was willing to consider, they were not used during the SDM process to evaluate management alternatives or identify information priorities.

1. *Maintain cooperative working relationships among jurisdictions managing mountain goats.*

   The working group recognized the importance of state and federal agencies working together and the importance of coordinating mountain goat management with tribal nations to the extent possible. The working group is committed to ensuring this happens in Montana, as evidenced by the interagency nature of this effort, and will continue interagency coordination into the future.

2. *Minimize negative impacts to goat habitat from human activities.*

   The working group recognized that human recreational (Côté 1996, Hurley 2004, Richard and Côté 2016, White and Gregovich 2018) and industrial development (Joslin 1986, White and Gregovich 2017) activities can negatively impact mountain goat habitat and habitat use. To date, given the limited recreation and development pressure experienced in mountain goat habitat across Montana, this has not been an overriding issue. The working group recognized the potential for this to occur in Montana, and they suggest that as pressures increase within individual mountain goat ranges that they be dealt with on a case-by-case basis.

3. *Minimize negative human-goat interactions.*

   Mountain goats can become habituated, leading to negative interactions and outcomes for mountain goats or people (Smith 2014, Sarmento and Berger 2017). Managing such negative interactions is a primary focus in Glacier National Park (e.g., https://www.nps.gov/articles/barkrangergracie.htm). Issues of mountain goat habituation are developing in some other herd ranges with substantial human recreation in Montana, for example the Bridger Mountains near Bozeman and areas west of Missoula. These issues need to be managed wherever they occur.

4. *Reduce impacts of conifer encroachment on goat habitat.*

   Conifer encroachment into the alpine habitat of mountain goats, as well as in some of the lower elevation habitats with rugged escape terrain that mountain goats inhabit, is a concern globally (Smith 2014) and in Montana (Smith and DeCesare 2017). As the working group discussed this issue, it became clear that due to the remote, rugged areas occupied by mountain goats, as well as federal wilderness designation, opportunities for managing conifer encroachment in Montana mountain goat habitat are very limited. These issues should be addressed through local management proposals and actions where warranted and possible, rather than being dealt with in a statewide strategy.

5. *Maximize public opportunity to view and hunt mountain goats.*

   "Contributing to the quality of life for present and future generations" is part of the FWP mission, as is "stewardship of the fish, wildlife, parks, and recreational resources of Montana." The working group recognized that viewing and hunting mountain goats is part of achieving these responsibilities for Montanans, to the extent that mountain goat populations and their habitat can withstand.

6. *Maximize public support for mountain goat conservation and management.*

   Public support and ownership of mountain goat populations and management efforts is required for mountain goat populations to be sustained in Montana. The working group recognized the need for outreach and public involvement everywhere that mountain goats live in Montana. This will ensure that mountain goat management efforts can be sustained over the long term.

Fundamental objectives

Fundamental objectives represent the mutually exclusive, complete set of desired outcomes that an ideal management strategy would accomplish. The working group defined fundamental objectives in detail, including specification of quantitative measurable attributes so that the effect of alternative management strategies could be predicted. The alternative management strategies considered by the working group differed in the degree to which they were predicted to meet each fundamental objective. The predicted ability of alternative management strategies to meet fundamental objectives formed the basis of the management recommendations produced by the working group.

1. *Maximize the number of occupied mountain goat population units.*

   Measurable attribute: square kilometers of suitable habitat that is occupied in 50 years

   This fundamental objective is focused on the future distribution of mountain goat populations in Montana. The term "population units" was used to describe hunting districts, National Parks, Reservations, or any other political boundary occupied by a mountain goat population. This objective does not refer to the relative density or distribution within an occupied population unit, but rather whether a mountain goat population functionally exists within the unit or not. This objective is forward looking, allowing the working group to consider the uncertain effects of climate change on the distribution of mountain goat populations. The time horizon of 50 years was chosen to balance a focus on the long time horizon for climate change with the practical need for some level of accuracy and precision in future predictions that are based on the world as it exists at present. This time horizon allowed the working group to consider mid-century climate predictions, which are a common output in many Global Climate Models.

2. *Maximize the number of mountain goat population units meeting objectives statewide, considering limitations in each population unit.*

   Measurable attribute: number of mountain goat population units meeting population trend objectives one generation from the present

   This fundamental objective is focused on mountain goat population dynamics within occupied population units. Information on mountain goat population sizes and demographics in Montana, much less habitat carrying capacity, is extremely limited (Smith and DeCesare 2017), so quantitative population objectives could not be set. Population trend objectives (i.e., declining, stable, or increasing) were defined to represent the general, desired direction for each mountain goat population (Table 1).

The mean mountain goat generation time (9 years; Festa-Bianchet and Côté 2008) was set as the time horizon for this objective. This time horizon balanced the need for reasonable precision in predictions, given the large uncertainty in mountain goat population sizes, demographics, and vital rates, with the fact that the effects of management actions on mountain goat population dynamics can take years to materialize because of their slow life history (Festa-Bianchet and Côté 2008).

Table 1. Population units, current population trends, and population trend objectives for areas currently occupied by mountain goats in Montana. Current population trends are as reported in Smith and DeCesare (2017) from an expert-opinion questionnaire, except for a subset of units for which members of the working group had since gathered new data indicative of change.

FWP Hunting District	Population Unit Name	Current Population Trend	Population Trend Objective
100	Cabinets	Decreasing	Increase
101	West Cabinets	Stable	Increase
131	Mission Mountains	Decreasing	Increase
132	Swan-Salmon	Uncertain	Increase
133	Swan-Clearwater	Decreasing	Increase
134	Swan-Bunker	Decreasing	Increase
140	Great Northern	Stable	Increase
141	Lower Middle Fork	Uncertain	Increase
142	Upper Middle Fork	Stable	Increase
150	Continental Divide	Stable	Increase
151	Danaher	Uncertain	Increase
212	Flint Range	Decreasing	Increase
213	Lost Creek	Decreasing	Increase
222	East Pintler	Decreasing	Increase
223	West Pintler	Decreasing	Increase
240	West Bitterroot	Stable	Increase
250	West Fork Bitterroot	Uncertain	Increase
261	Sapphire Range	Uncertain	Increase
270	East Fork Bitterroot	Uncertain	Increase
280	North Blackfoot	Stable	Increase
312	Pioneers	Stable	Increase
313	Crazy Mountains	Decreasing	Stable
314	Gallatin Range	Stable	Stable
316	Cooke City	Stable	Stable
320	Tobacco Roots	Increasing	Increase
321	Medicine Lodge-Big Sheep	Uncertain	Increase

FWP Hunting District	Population Unit Name	Current Population Trend	Population Trend Objective
322	South Big Hole	Increasing	Increase
323	South Absaroka	Stable	Stable
324	Spanish Peaks	Stable	Stable
325	Jack Creek-Indian Creek	Increasing	Increase
326	Indian Creek-Wolf Creek	Increasing	Increase
327	Wolf Creek-Papoose Creek	Increasing	Increase
328	Papoose Creek-Rock Creek	Decreasing	Increase
329	Hellroaring Creek - Slough Creek	Stable	Stable
330	North Absarokas	Stable	Stable
331	Snowcrest Mountains	Stable	Increase
332	Sleeping Giant	Uncertain	Increase
340	Highland	Stable	Increase
361	Hebgen - Upper Madison	Increasing	Increase
362	Cabin Creek	Increasing	Stable
380	Radersburg (Elkhorns)	Stable	Increase
393	Bridger Mountains	Stable	Increase
414	North Teton	Uncertain	Increase
415	Birch Creek	Stable	Increase
442	South Teton	Stable	Increase
447	Square Butte	Stable	Increase
453	South Big Belts (Mt. Edith)	Uncertain	Increase
460	Highwoods	Stable	Increase
514	Line Creek	Decreasing	Stable
517	Rock Creek	Decreasing	Stable
518	Froze-to-Death	Stable	Stable
519	Fishtail	Stable	Stable
N/ A	Rattlesnake	Uncertain	Increase
N/ A	Great Burn	Uncertain	Increase
N/ A	Sun River Game Preserve	Stable	Increase
N/ A	North Big Belts	Increasing	Increase
N/ A	Big Snowy	Uncertain	Increase
N/ A	Glacier National Park	Stable	Stable

3. *Minimize disease risks to bighorn sheep.*

   Measurable attribute: risk value function composed of elements representing the number of bighorn sheep herds that overlap mountain goat herds with pneumonia-associated pathogens and the number of bighorn sheep herds being mixed with mountain goat herds in management actions

The working group considered impacts on native plant communities, competition with sympatric bighorn sheep, and spreading pneumonia-associated pathogens to bighorn sheep as possible ecosystem impacts of mountain goats. Mountain goats introduced outside of their native range have negatively impacted native alpine plant communities in some areas, for example Olympic National Park (Houston et al. 1994). However, mountain goats introduced onto the northern range of Yellowstone National Park are unassociated with plant community composition or vegetation cover there (Aho 2012). The working group was not aware of this concern in other areas in Montana where mountain goats were introduced outside of their native range.

DeVoe et al. (2015) found a wide distribution of mountain goats with additional potential unoccupied habitat, and Flesch et al. (2016) found substantial recent population growth and range expansion in the Greater Yellowstone Ecosystem. Lowrey et al. (2018b) found substantial niche overlap of sympatric, introduced mountain goats and native bighorn sheep in the Greater Yellowstone Ecosystem. These findings highlight the potential for resource competition between sympatric mountain goats and bighorn sheep. However, Flesch and Garrott (2013) found that bighorn sheep population growth was not negatively impacted by sympatry with mountain goats in these same areas, indicating that if resource or direct competition does occur it has not resulted in population-level effects.

Therefore, with regards to limiting the negative effects of mountain goats on the ecosystems they inhabit, the working group specified this objective to focus on disease implications to sympatric bighorn sheep. Lowrey et al. (2018a) found that mountain goats and bighorn sheep populations harbor similar respiratory pathogen communities. These respiratory pathogen communities are associated with epizootic die-off events in bighorn sheep across North America (Cassirer et al. 2018). First principles of epidemiology dictate that pathogen presence alone does not induce disease epidemics; host and environmental factors also play a role (Gullis and Fujino 2015). Bighorn sheep pneumonia epidemics in Montana are associated with several additional risk factors (Sells et al. 2015), and there is substantial overlap in recruitment rates of bighorn sheep populations with and without known presence of various pneumonia-associated pathogens (Butler et al. 2018). This objective is therefore intended to represent the risk associated with pneumonia outbreaks that comes specifically from pathogen presence, notwithstanding other host or environmental factors that may be required for disease expression.

The measurable attribute associated with this fundamental objective is a composite measure, defined as

$$Bighorn\ Sheep\ Risk\ Value = KP_{BHS} + (M * NM_{BHS-MG}),$$

Where KP_{BHS} is the predicted total number of bighorn sheep herds in Montana that overlap mountain goat herds with pneumonia-associated pathogens; M is a subjective value associated with pneumonia risk generated from mixing microbial pathogen communities among the mountain ungulate herds involved in transplants; and NM_{BHS-MG} is the number of bighorn sheep herds being mixed with mountain goat herds as the result of transplants under different management alternatives.

Separate consideration of the number of bighorn sheep and mountain goat herds being mixed stems from the polymicrobial nature of pneumonia epizootics (Cassirer et al. 2018) and the possibility of multiple pathogen strains, variable pathogenicity, and strain-specific immunity in bighorn sheep herds (Cassirer et al. 2017). Mountain goat transplants into areas occupied by bighorn sheep involve mixing the microbial communities living in the transplanted mountain goats with those living in the resident bighorn sheep. Mountain goat transplants might therefore initiate an epizootic in sympatric bighorn sheep, if the right combination of pathogens or different strains of pathogens are mixed among the hosts.

Ecological and etiological complexities and uncertainties hinder a comprehensive understanding of the microbial causes of pneumonia in bighorn sheep (Cassirer et al. 2018). We added the risk multiplier (M) for mixing of microbial communities as an expression of risk tolerance for this uncertainty among the working group. Risk tolerance is an individual, value-based attribute that must be accounted for in decision-making (Goodwin and Wright 2014). Higher values of this multiplier and a larger number of mountain goat herds being mixed with bighorn sheep herds would increase the measure of the bighorn sheep risk value function beyond solely the number of bighorn sheep herds exposed to mountain goat herds with pneumonia pathogens.

4. *Minimize disease risks to mountain goats.*

   Measurable attribute: risk value function composed of elements representing the number of mountain goat herds with pneumonia-associated pathogens and the number of mountain goat herds being mixed with mountain goat or bighorn sheep herds in management actions

   Recent evidence indicates that the same respiratory pathogens that cause pneumonia epizootics in bighorn sheep can also cause pneumonia epizootics in mountain goats

(Wolff et al. 2014, Anderson et al. 2016, Lowrey et al. 2018a). The working group therefore applied the same logic used to develop the measurable attribute for fundamental objective number 3 to this fundamental objective. The measurable attribute associated with this fundamental objective is a composite measure, defined as

$$Mountain\ Goat\ Risk\ Value = KP_{MG} + (M * NM_{MG-BHS-MG}),$$

Where KP_{MG} is the predicted total number of mountain goat herds in Montana with pneumonia-associated pathogens; M is a subjective value associated with pneumonia risk generated from mixing microbial pathogen communities among the herds involved in transplants; and $NM_{MG-BHS-MG}$ is the number of mountain goat herds being mixed with resident mountain goat or bighorn sheep herds in transplants.

5. *Minimize cost.*

   Measurable attribute: predicted annual costs (in dollars) of management alternatives

   This fundamental objective is straightforward. Because of limited funding and within-agency competition for funding of multiple other priorities, costs need to be kept as low as possible. Itemized costs of past management actions were used to predict the costs of possible future management actions.

6. *Minimize social conflict resulting from mountain goat management.*

   Measurable attribute: constructed 1-5 scale (none, low, medium, high, extreme) representing the extent of conflict created by management actions

   The working group recognized that many management actions to improve the status of mountain goats potentially conflict with other societal objectives for wildlife, agriculture, economic development, or recreation. Because quantification of the relative degree of conflict created by management actions would be a complicated social science endeavor and beyond the timeframe of this process, the 1-5 constructed scale was created. Working group members were asked to use their professional judgement and experience to predict the consequences of each management action on this constructed, relative scale.

Alternatives

The working group created alternatives in two phases. In the first phase, the working group created a set of 5 strategies composed of distinct and non-overlapping actions. The working group then predicted the consequences of these 5 mutually exclusive strategies relative to each fundamental objective. In the second phase, the working group discussed the predicted consequences, the associated tradeoffs, and the relative performance of these 5 strategies to combine elements of each of the 5 mutually exclusive strategies into 2 additional, combined strategies. The working group therefore considered a total of 7 alternative strategies for mountain goat management.

These 7 strategies are intended as examples of possible management actions, and their primary use was to provide guidance on more general management recommendations and identify priority information needs. Each alternative strategy considered by the working group is specified to a high level of detail. This was required to predict the consequences of each strategy relative to each fundamental objective, a necessary step in the SDM process to provide management guidance and identify priority information needs. However, the elements associated with each strategy do not represent the only possible elements or locations where the strategies could be implemented. The management recommendations stemming from evaluation of these strategies are therefore not as specific as the strategies that were evaluated.

Alternative 1: Status quo strategy

The status quo strategy is focused on population monitoring and conservative harvest management. The monitoring program as well as the recent, conservative trajectory of the harvest management program is described in greater detail in Smith and DeCesare (2017). Limited aerial monitoring of mountain goat herds is conducted around Montana, and trend counts have been conducted on a regular basis in 21 of 58 mountain goat population units. Additionally, since 2016, an annual effort has been made to survey for respiratory pathogens of bighorn sheep and mountain goat herds by capturing and testing a statistically robust sample of animals in select herds (target of 1 herd/year). In terms of harvest management, the number of mountain goat licenses issued has decreased since the 1960s, primarily within the native range of mountain goats. Over 90% of hunting opportunity currently occurs in herds that were introduced by FWP outside of their native range within Montana. As of 2017, hunting seasons had been eliminated in 12 of 52 mountain goat hunting districts, 9 of which were within the native range of mountain goats. The trend toward reducing harvest pressure continued into the 2018 season, when the closure of 7 more native districts resulted in mountain goat hunting opportunity being largely eliminated across the Bob Marshall Wilderness Complex. Additionally, a regulation went into effect eliminating harvest opportunity for nanny mountain goats in groups containing one or more kids in most of the herds within the native range.

Alternative 2: Top-down mortality management strategy

This strategy builds on the status quo strategy by further limiting mortality from harvest as well as predation from carnivores. The dynamics of small mountain goat populations are extremely sensitive to human harvest, particularly harvest of nannies (Hamel et al. 2006). Under this alternative, harvest mortality would be further reduced from the status quo strategy by reducing nanny harvest in hunting districts where the population is currently stable or declining but the trend objective is for an increasing herd (Table 1). The exact regulation by which nanny harvest would be reduced was not specified but could differ based on conditions in each herd range, and may include male-only harvest, disallowing hunting of nanny goats in groups with kids, or other regulations.

Under this alternative, mortality from carnivores would also be reduced by increasing public opportunity to harvest carnivores to reduce carnivore densities within the range of certain mountain goat herds where the population is currently stable or declining but the trend objective is for an increasing herd. Festa-Bianchet et al. (1994) found that carnivore predation limited kid recruitment in a central Alberta mountain goat population, with similar levels of mortality attributed to mountain lions, wolves, and grizzly bears. A study in southeast Alaska found roughly equivalent mortality rates due to human hunting, predation (wolf and bear), and non-predation natural causes (Smith 1986). No other data exist on the effect of predation or carnivore-specific mortality on mountain goat populations. The working group therefore focused on mountain lions and wolves for the reductions in carnivore densities within certain mountain goat herd ranges associated with this alternative. These reductions in mountain lion or wolf density would be accomplished through hunting and trapping regulations for these carnivores. Grizzly bears in the continental USA are listed as Threatened under the Endangered Species Act, and their densities cannot be managed through hunting or trapping. The exact mountain lion and wolf hunting or trapping regulations to reduce local densities were not enumerated but could include, for example, directing hunters to specific mountain goat herd ranges under current regulations, liberalizing existing hunting or trapping regulations within mountain goat herd ranges, or creating new, localized hunting districts or special management areas with liberal opportunities in mountain goat herd ranges. Both mountain lion (Robinson et al. 2014) and wolf (Hayes et al. 2003) densities can be reduced in local areas over defined time periods through increased human-caused mortality. During or following cessation of high levels of human-caused mortality, local wolf (Adams et al. 2008) and mountain lion (Robinson et al. 2014, Robinson et al. 2015) population dynamics can increase rapidly due to immigration and emigration. At the same time, dynamics of their populations over larger areas are less affected by harvest, immigration, and emigration in local areas (Adams et al. 2008, Robinson et al. 2015). Increased carnivore harvest within mountain goat herd ranges could therefore be implemented in a way that reduces local wolf or mountain lion populations while conserving their populations over larger ecoregions, entirely consistent with Montana wolf (Montana FWP 2004) and mountain lion (Montana FWP 2019) management plans. Whether carnivore density reductions in local areas (specific mountain goat herd ranges) are socially acceptable or will translate into increased recruitment in mountain goats is unknown, but possible based on experience with other ungulates (Hayes et al. 2003, Proffitt et al. in review).

Alternative 3: Introduction strategy

This alternative builds upon the status quo strategy by introducing new mountain goat populations. For the purposes of this exercise, the working group defined a set of 5 introductions of new populations where mountain goats currently do not exist (Table 2). Considerable local discussion and public process would be needed before any of these possible translocations were officially proposed or began moving forward. These introductions would occur over a series of years rather than proceeding all at once. These new populations would be in a combination of areas that likely have abundant mountain goat habitat as well as some areas with less predicted habitat, which would be considered experimental. The working group thought that an experimental introduction would help elucidate the extent to which the current understanding of mountain goat habitat requirements was correct and speed learning about the extent to which lower-elevation mountain goat habitat might become marginal with climate change. Also, the working group identified the potential source for a reintroduction into the Whitefish Range as Glacier National Park. This was to ensure that respiratory pathogens within a newly-introduced Whitefish Range mountain goat population were the same as those already existing in the adjacent Glacier National Park mountain goat population, to limit the potential pneumonia epizootic risk among nearby bighorn sheep or mountain goat populations. Similar thought was given to the concept of sourcing a new population in the Northwest Peaks area from Idaho. Any possible movement of mountain goats from Glacier National Park to sites outside the park, or obtaining mountain goats for translocations from anywhere outside of State of Montana jurisdiction, would require extensive coordination with the other jurisdiction before being proposed and would entail a public review and comment period. Any transplant with an identified source from outside of State of Montana jurisdiction should be considered as being sourced from outside of Montana more generally, rather than from a specific location.

Table 2. New introductions of mountain goat populations considered under the Introduction strategy. Considerable local discussion and public process would be needed before any of these possible translocations were officially proposed or began moving forward.

New herd establishment area	Number used to establish herd	Proposed source herd units and hunting districts		Number removed, per herd unit
Whitefish Range	50	Glacier National Park[1]		-50
Little Belt Mountains	50	Crazy Mountains	HD 313	-50
Gravelly Mountains	50	Gallatin Range	HD 314	-20
		Spanish Peaks	HD 324	-20
		Cabin Creek	HD 362	-10
Northwest Peaks	50	Idaho[1]		--
Sweet Grass Hills	50	South Absaroka	HD 323	-50

[1] For transplants sourced from outside of State of Montana jurisdiction, more extensive coordination would be required with the other jurisdiction before being proposed. For now, such transplants should be interpreted as being sourced from outside of State of Montana jurisdiction rather than from a specific jurisdiction or population.

Alternative 4: Augmentation strategy

This alternative builds upon the status quo strategy by conducting augmentations into struggling mountain goat herds. In considering this strategy, the working group specified pre-planning activities that would need to occur prior to implementing each augmentation. A formal risk assessment would be produced for agency staff, the public, and decision-makers to consider. This risk assessment would consist of (1) assessing body condition and respiratory pathogens in source and recipient herds by capturing and handling a sufficient sample of animals, (2) surveying directly after kidding season (prior to predation mortalities) to assess kid production if captures to assess body condition are infeasible, and (3) assessing the historical harvest regime for mountain goats and carnivores in the recipient area to determine the likelihood that harvest or predation has limited the population to its current, struggling state. The working group noted that there currently is not a published, accepted method for assessing and reporting differences in body condition among mountain goat herds. One is under development, based on assessments of mountain goats being removed from Olympic National Park, so the method could be available in the future.

Regardless, full risk assessments would not be possible in each proposed source and recipient herd, and even where they were possible, they would not produce perfect knowledge. The proposed augmentations would proceed if the potential benefit was deemed worth the risk by the individual herd managers in the source and recipient areas, FWP agency officials, and the Montana Fish and Wildlife Commission, given the imperfect knowledge assembled in the risk assessment. Involvement of herd managers in both source and recipient areas in this decision making process would be crucial, so that potential gains and losses in both areas are considered.

The working group identified a set of 7 augmentations for consideration as part of this strategy (Table 3). Recipient herds for these augmentations were chosen because they are struggling populations where hunting opportunity for mountain goats has been eliminated. Source populations were identified as populations that are thriving or sufficiently large in Montana, or where depopulation efforts are underway outside of Montana. Multiple source herds were not mixed into a single recipient area to avoid further mixing of respiratory pathogen communities among source herds. Considerable local discussion and public process would be needed before any of these possible translocations were officially proposed or began moving forward.

Genetic attributes of source or recipient herds were discussed and explicitly not considered by the working group. The limited information available on the relationship between population dynamics and genetic characteristics suggests that genetic attributes are not related to population growth (Ortega et al. 2011). The working group could not identify any data indicating that certain genetic attributes of mountain goat herds are undesirable or detrimental to mountain goat population dynamics.

Table 3. Augmentations of mountain goat populations considered under the Augmentation strategy. Considerable local discussion and public process would be needed before any of these possible translocations were officially proposed or began moving forward.

Recipient herd	Total number used for augmentation	Recipient hunting districts	Number augmented, per hunting district	Proposed source herd units and hunting districts		Number removed, per hunting district
Mission Mountains	50	HD 131	50	Grand Teton National Park[1]		--
Swan Range	50	HD 132 HD 134	25 25	South Absaroka	HD 323	-50
Bitterroot Mountains	100	HD 240 HD 250	75 25	Olympic National Park[1]		--
Pintler Range	80	HD 222 HD 223	40 40	Olympic National Park[1]		--
Flint Range, Lost Creek	40	HD 212 HD 213	20 20	Olympic National Park[1]		--
Beaverhead Mountains	50	HD 321	25	Spanish Peaks	HD 324	-30
		HD 322	25	Cabin Creek	HD 362	-20
Rocky Mtn Front	50	HD 414 HD 442	25 25	Gallatin Range	HD 314	-50

[1] For transplants sourced from outside of State of Montana jurisdiction, more extensive coordination would be required with the other jurisdiction before being proposed. These areas were identified based on current depopulation efforts, which may not continue long enough for implementation of the recommendations stemming from this SDM process. For now, such transplants should be interpreted as being sourced from outside of State of Montana jurisdiction rather than from a specific jurisdiction or population.

Alternative 5: Habitat protection strategy

Building from the status quo strategy, this strategy focused on protecting important, seasonal mountain goat habitats from human use to limit disturbance. Mountain goat distribution can be very sensitive to human disturbance from motorized and non-motorized recreation, aerial activity, mineral development, and other economic development (Festa-Bianchet and Côté 2008). If these activities take place within core mountain goat habitats, mountain goat access to those habitats is lessened, and the working group assumed that this would translate into negative effects on mountain goat reproduction and survival. Under this alternative, these activities would be limited or excluded on public lands within mountain goat wintering, summering, and kidding areas in mountain goat population units that are stable or declining but have an increasing population trend objective (Table 1).

Alternative 6: Combined strategy, with augmentations

This alternative combined elements of each of the previous strategies. The elements in this strategy were chosen based on the relative performance of the previous strategies at achieving certain fundamental objectives, and actions that herd managers wanted to evaluate in certain herds were also included. This strategy builds from the status quo strategy by further reducing nanny harvest in herds with a decreasing population trend objective that are not meeting that objective (Table 1). In addition, public harvest of carnivores would be increased within the range of certain mountain goat herds where the population is not meeting the population trend objective for an increasing herd, and around some new introductions. These include mountain goat herds in the Cabinet Mountains, Thompson Falls area (new introduction), the Flint Range, several herds in the Bitterroot Mountains and watershed, the Sapphire Mountains, the Great Burn area, the east and west Pintler Range, all of FWP Region 3 (i.e., hunting district numbers beginning with a 3) where there is an increasing trend objective but herds are not meeting that objective, the Highwoods, Square Butte, north and south Big Belt mountains, and the Little Belt mountains (new introduction). The working group identified 3 areas where new introductions of mountain goat herds would occur and 5 areas where augmentations would occur into struggling mountain goat herds, following the risk assessment procedures described in Alternative 4 (Table 4). Restrictions on human activities, as detailed in Alternative 5, would be limited only to specific mountain goat seasonal habitats with known or predicted conflicts to maintain current reproductive rates, as National Forest planning opportunities arise, and these restrictions were therefore not forecasted to impact mountain goat population dynamics.

Table 4. New introductions and augmentations of mountain goat populations considered under the Combined strategy, with augmentations. Considerable local discussion and public process would be needed before any of these possible translocations were officially proposed or began moving forward.

Transplant type	Recipient herd	Total number used for transplant	Recipient hunting districts	Number released, per hunting district	Proposed source herd units and hunting districts		Number removed, per herd unit
Introduction	Whitefish Range	50	--	50	Glacier National Park[1]		-50
Introduction	Little Belt Mountains	50	--	50	Crazy Mountains	HD 313	-50
Introduction	Thompson Falls	50	--	50	Gallatin Range	HD314	-50
Augmentation	Pintler Range	50	HD 222 HD 223	25 25	South Absaroka	HD323	-50
Augmentation	Mission Mountains	50	HD 131	50	Olympic National Park[1]		--
Augmentation	Swan Range	50	HD 132 HD 134	25 25	Glacier National Park		-50
Augmentation	Bitterroot Mountains	100	HD 240 HD 250	75 25	Olympic National Park[1]		--
Augmentation	Sapphire Range, East Fork	50	HD 261 HD 270	15 10	Grand Teton National Park[1]		--

[1] For transplants sourced from outside of State of Montana jurisdiction, more extensive coordination would be required with the other jurisdiction before being proposed. Some of these areas were identified based on current depopulation efforts, which may not continue long enough for implementation of the recommendations stemming from this SDM process. For now, such transplants should be interpreted as being sourced from outside of State of Montana jurisdiction rather than from a specific jurisdiction or population.

Alternative 7: Combined strategy, without augmentations

The working group specified this strategy to be the same as the *Combined strategy, with augmentations* (Alternative 6), with the exception being that the 5 augmentations (Table 4) would not occur. This strategy was specified based on the relative predicted performance of the *Combined strategy, with augmentations* at meeting fundamental objectives.

Consequence predictions

Decision analysis requires explicit predictions of the effect of each alternative on each fundamental objective, on the scale of the measurable attributes. Few mountain goat data are available in Montana, and considerable uncertainty surrounds most mountain goat ecological and disease processes. The science team constructed multiple alternative models to predict the effect of alternatives on fundamental objectives for which considerable uncertainty exists. These alternative models were constructed to contain the range of variability and uncertainty relevant to each fundamental objective, so the inherent uncertainty could be considered by the working group in developing their recommendations. For each fundamental objective where uncertainty was incorporated into the consequence predictions, the working group also had to specify a belief (or probability) weight on the predictions from each alternative model.

Predictions for the area of suitable habitat that will be occupied by mountain goat populations in 50 years

The primary uncertainty surrounding the area that will be occupied by mountain goat population units in Montana into the future is related to the impact that climate change will have on suitable habitat for mountain goats. Small-scale behavioral research in Glacier National Park suggests that mountain goats use snow to slow their respiration during summer (Sarmento et al. 2019). Within-seasonal-range habitat selection modeling for individual mountain goats in southeastern Alaska indicates selection for alpine habitat characteristics that are likely to shrink in extent in the future due to climate change (White and Gregovich 2017, White et al. 2018). Individual mountain goat survival is also negatively correlated to high temperatures during summer and lower snowfall during winter in southeast Alaska, and mountain goat survival and populations are likely to decrease there in the future (White et al. 2011, White et al. 2018). However, results from individual study areas or studies focused on specific ecological details do not always translate effectively to other areas or to the larger scales and variable conditions related to management decisions (Morrison 2012, Hiers et al. 2016).

The working group was concerned with the distribution of mountain goat populations throughout Montana into the future. Mountain goat populations occur over rugged, remote areas in western Montana and some island mountain ranges of central Montana. While climate change may limit the extent of their habitat, the existence of mountain goat populations in some warmer and drier parts of Montana (e.g., Square Butte) and in other regions (e.g., the Black Hills in South Dakota and several herds in Nevada) suggests that climate change may not strictly limit the distribution of mountain goat populations in Montana into the future.

We used a second order (population-level) Resource Selection Function (RSF) modeling approach with a used-unused design to estimate the probability that western and central Montana can support mountain goat populations (Manly et al. 2002). We sampled 10,000 random points within the current distribution of mountain goat populations (Figure 1) to reflect current used conditions. To reflect unused conditions, we sampled 100,000 random points from the remainder of FWP Administrative Regions 1-5, which currently encompass all mountain goat populations in Montana, outside of the polygons defining current mountain goat distribution. To represent uncertainty about the degree to which climate change will limit the distribution of mountain goat populations in 50 years, we fit two separate RSF models, one that included only covariates that were not climate-related and one that included climate-related covariates.

All covariates were resampled to a 300-meter square resolution, given the large scale of the desired inference about the future distribution of mountain goat populations. Covariates considered in the modeling process included elevation, slope, slope variance (estimated at 30m pixels, then averaged over 300m), canopy cover, cumulative winter snow water equivalent (estimated from SNODAS; https://nsidc.org/data/g02158), precipitation (climate-related covariate), growing degree days (climate-related covariate), mean winter temperature (climate-related covariate), and potential vegetation type (forest, alpine tundra, or other; climate-related covariate).

We screened for collinearity among covariates and excluded covariates with correlation coefficients >0.6 from the same model, according to univariate significance. We then used a manual, backward-stepping model selection procedure to identify the best non-climate-related and climate-related models (that included climate-related covariates). We validated the top non-climate-related and climate-related models using k-folds validation, withholding 5 partitions of data and assessing the correlation between model predictions and the prevalence of used locations.

Following model selection, the top non-climate-related model included the covariates canopy cover and slope (Figure 3). The 5-fold cross validation revealed that used locations were consistently located in areas predicted to be in high quality habitat under this model, and the spearman rank test showed significant alignment between predictions and data, indicating high model accuracy (Spearman rho=0.99, P < 0.0001, Figure 4). The top climate-related model included the covariates canopy cover, slope, precipitation, growing degrees days, and potential vegetation (Figure 5). The 5-fold cross validation revealed that this model also fit the data well. Used locations were consistently located in areas predicted to be in higher quality habitat, and the spearman rank test showed significant alignment between predictions and data (Spearman rho=0.99, P < 0.0001, Figure 6).

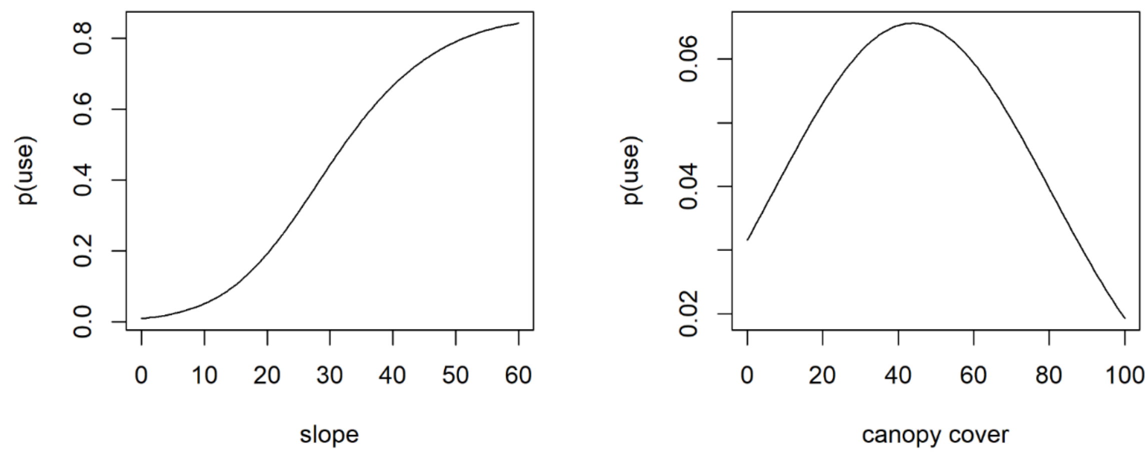

Figure 3. Estimated covariate effects on the probability of habitat use by mountain goat populations in Montana from the top non-climate-related Resource Selection Function model.

To represent climate change uncertainty over the next 50 years, we used mid-century spatial projections from 3 Global Climate Models (GCMs) to forecast mountain goat habitat conditions using the model with climate-related coefficients. The three global climate models we used included the CanESM2, the CCSM4, and the IPSL-CM5A-MR models. These climate models were selected to represent climate change scenarios from dozens of possible GCMs because each is in the top tier of predictive accuracy within the Rocky Mountains and Pacific Northwest (Rupp et al. 2013).

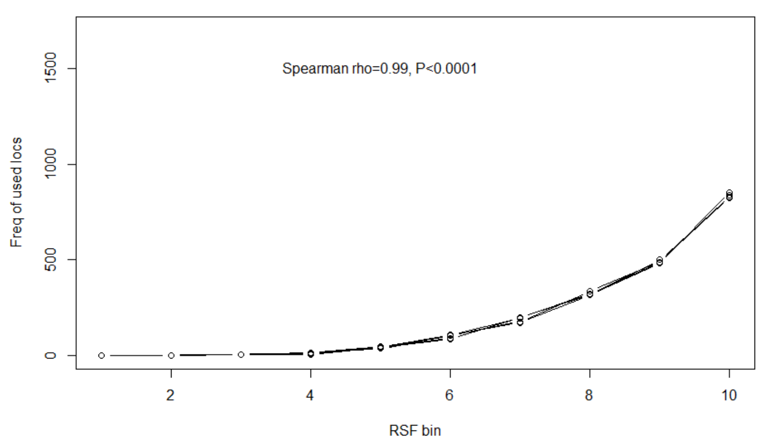

Figure 4. Five-fold cross validation results for the top non-climate-related model of habitat use by mountain goat populations in Montana. Consistently more withheld used locations were in high quality Resource Selection Function (RSF) bins, indicating good model accuracy.

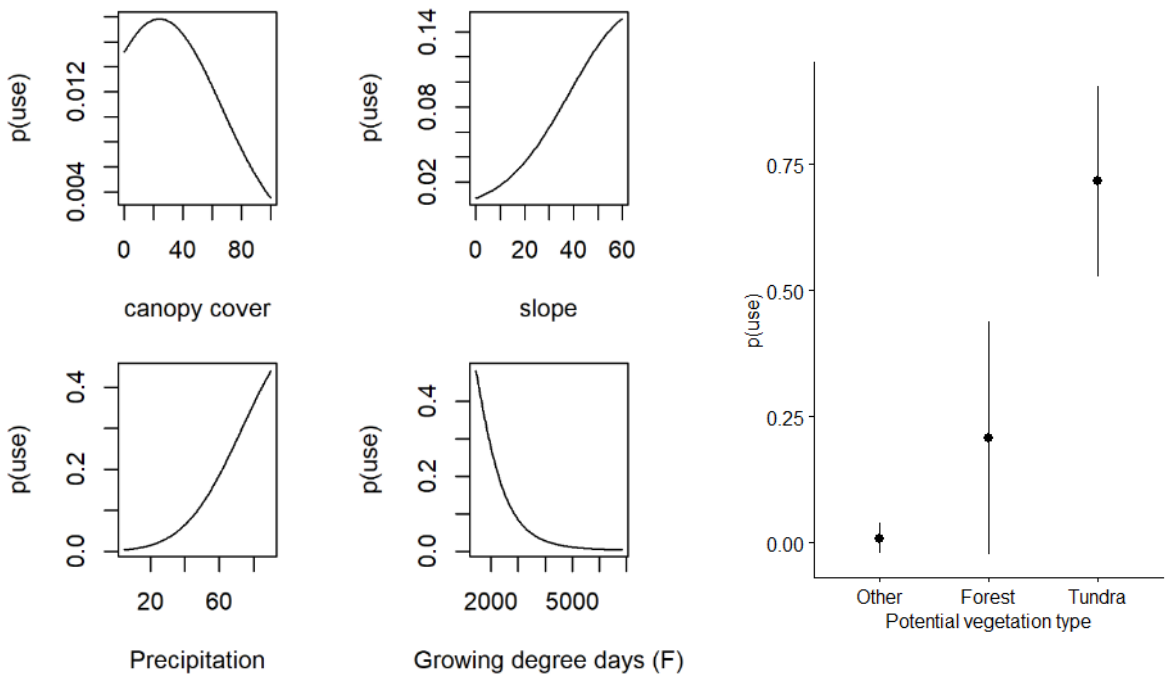

Figure 5. Estimated covariate effects on the probability of habitat use by mountain goat populations in Montana from the top climate-related Resource Selection Function model.

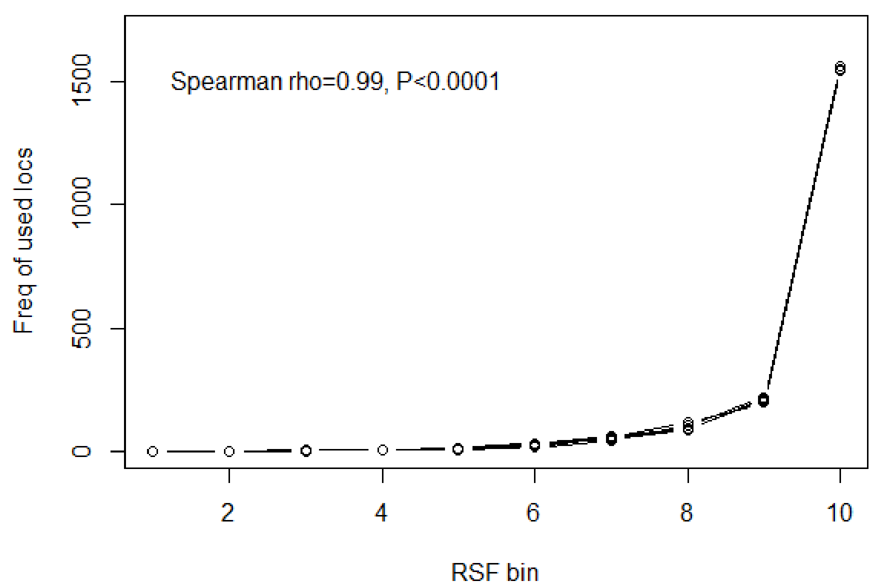

Figure 6. Five-fold cross validation results for the top climate-related model of habitat use by mountain goat populations in Montana. Consistently more withheld used locations were in high quality Resource Selection Function (RSF) bins, indicating good model accuracy.

These 3 models also represent a wide range of potential mid-century temperature and winter precipitation scenarios for the Pacific Northwest, including very hot and very wet (CanESM2), hot and very dry (CCSM4), and very hot and wet (IPSL-CM5A-MR; Figure 7, Figure 8). Projections from these models were made using Representative Concentration Pathway 8.5 for greenhouse gas emissions, which represents the high carbon emissions scenario into the future. The high emissions scenario was the only scenario used, to maximize the contrast between the climate-related RSF model and the non-climate-related RSF model. However, projected mid-century climate responses, as opposed to late-century responses, are less sensitive to the choice of emission scenario.

This modeling process thereby produced 4 separate predictions representing the range of uncertainty about whether and how climate change will limit the distribution of mountain goat populations in 50 years in Montana (Figure 9). One model contained no climate-related covariates and represented the hypothesis that climate change will not limit the distribution of mountain goat populations. We then forecasted the potential effects of climate change on the distribution of habitat that can support mountain goat populations during 2040-2069 (mid-century, median year 2055) using the projected precipitation, growing degrees days, and potential vegetation type spatial data layers from the three GCMs to generate RSF predictions from the top climate-related RSF model.

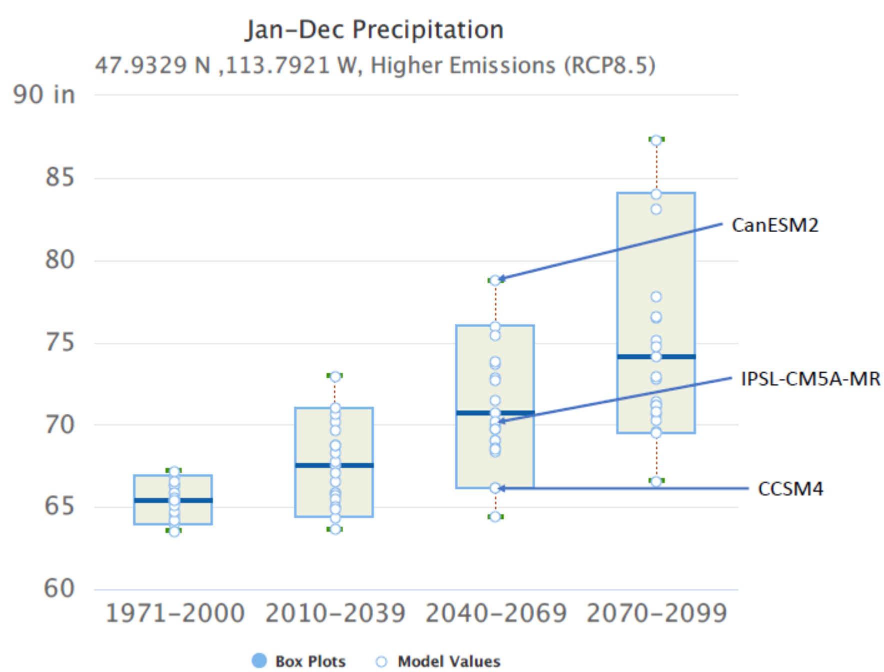

Figure 7. Historical and predicted annual precipitation values generated by Global Climate Models (GCMs) covering the Pacific Northwest, under Representative Concentration Pathway (RCP) 8.5 that assumes high future carbon emissions. Mid-century predictions for the GCMs used for this analysis are highlighted. This figure was generated from the Pacific Northwest Climate toolbox (https://toolkit.climate.gov/tool/northwest-climate-toolbox).

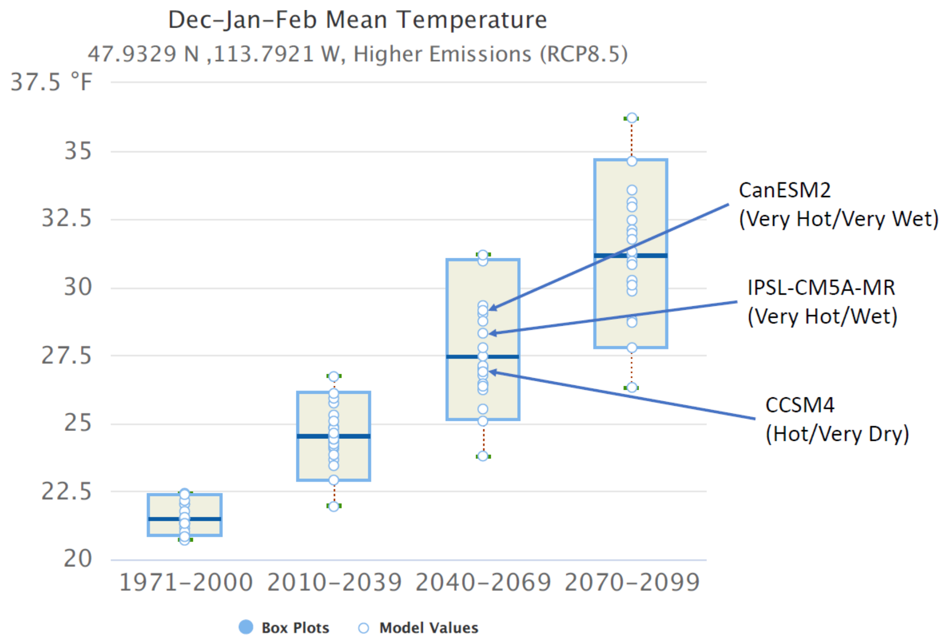

Figure 8. Historical and predicted winter temperature values generated by Global Climate Models (GCMs) covering the Pacific Northwest, under Representative Concentration Pathway (RCP) 8.5 that assumes high future carbon emissions. Mid-century predictions for the GCMs used for this analysis are highlighted. This figure was generated from the Pacific Northwest Climate toolbox (https://toolkit.climate.gov/tool/northwest-climate-toolbox).

Incorporating uncertainty represented by multiple models into decision analysis requires model weights for multi-model inference (Conroy and Peterson 2013). In terms of the influence of climate change on habitat use by mountain goat populations, no empirical data exist on the relative predictive accuracy of models with and without climate-related covariates, on which to base model weights. We therefore elicited belief weights from the working group and science team regarding whether climate change will influence the future distribution of mountain goat populations, as represented by our two RSF models (one with non-climate-related covariates and the other with climate-related covariates). We elicited belief weights using a likelihood point method, in which each participant distributed 100 points according to their personal belief that climate-related covariates (and therefore climate change) will or will not limit the future distribution of mountain goat populations in Montana. The points allocated to each of the two models were then divided by 100 to obtain a relative probability weight for each model for each participant, and these values summed to 1 for each participant. We used a modified Delphi method for this elicitation (Clark et al. 2006). After completing the exercise, participants were shown individual and group results, discussed differing probability weights and their rationale, and were given the opportunity to change their values. The overall mean relative probability weight for each model was then used to represent the group belief weight in the non-climate-related and climate-related models, resulting in a weight of 0.39 on the top non-climate-related model and 0.61 on the top climate-related model. Following standard practice in climate forecasting, the total belief weight in the top climate-related model was split equally

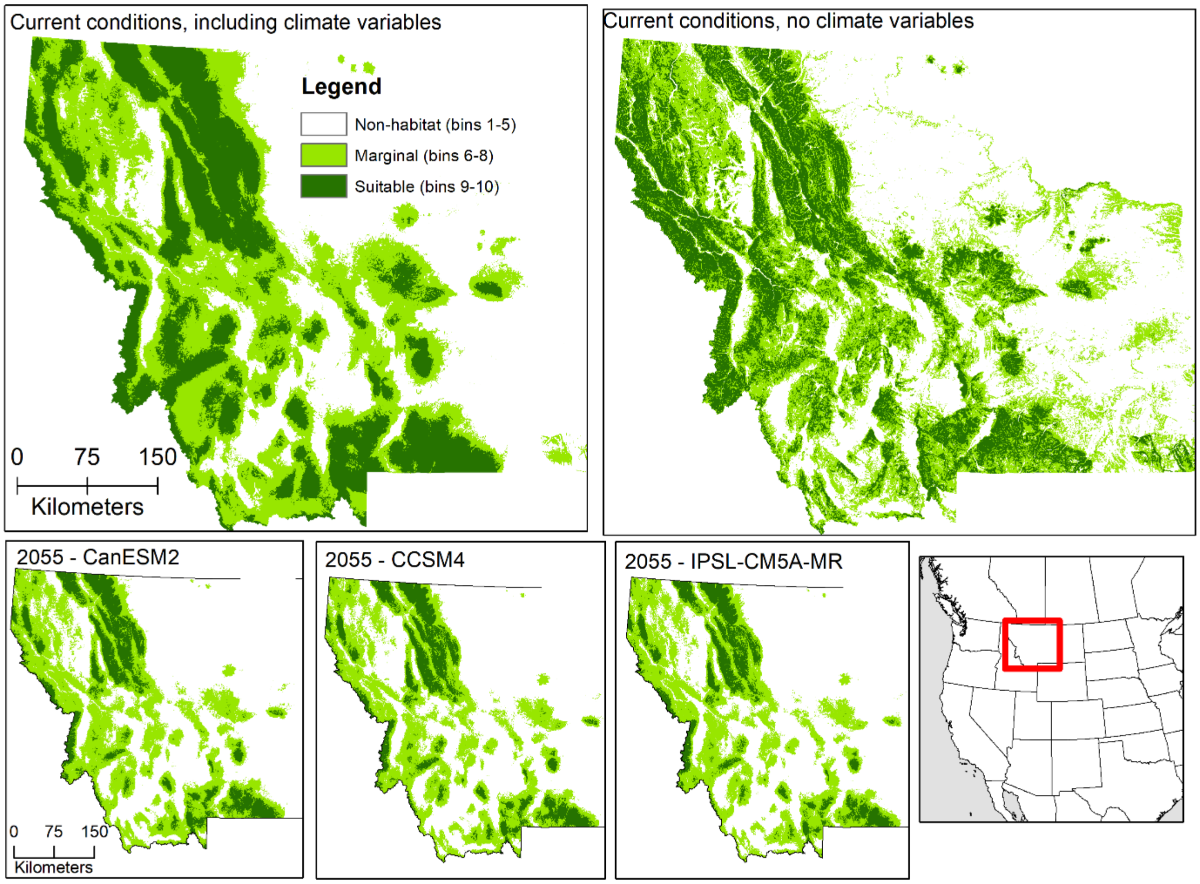

Figure 9. Maps depicting the top non-climate-related and climate-related Resource Selection Function (RSF) models for habitat that can support mountain goat populations in Montana (top 2 panels) and the mid-century predictions for habitat that can support mountain goat populations in Montana based on incorporating forecasts from 3 divergent Global Climate Models (GCMs) into the top climate-related RSF model (bottom 3 panels). In each map, RSF models were divided into 10 equal-area bins, and these 10 bins were subsequently grouped into values representing suitable (white), marginal (gray), and non-habitat (black). For decision analysis incorporating uncertainty about if and how climate change will impact the future distribution of habitat that can support mountain goat populations, the top non-climate-related RSF (top right panel) and the 3 alternative predictions representing possible climate change effects (bottom 3 panels) were used.

among the 3 forecasts stemming from the divergent GCMs, for equal weights of 0.204 on the predictions from each GCM projection.

In each RSF model, we divided predictions into 10 equal-area bins, and these 10 bins were then subjectively grouped into values representing suitable (bins 9 and 10; the top predicted RSF values), marginal (bins 6-8), and non-habitat (bins 1-5). The suitable habitat bin was defined to contain only bins 9 and 10 because these bins contained 85.0% of the used locations sampled from our current mountain goat distribution layer for the top climate-related RSF model. We next used the top non-climate related model and the top climate-related RSF model to predict the area of suitable habitat that will exist in 2055 (the midpoint of the 2040-2069, mid-century climate forecasts) in each mountain goat population unit (Table 5). Areas of suitable yet unoccupied habitat represent areas with the potential for establishing new mountain goat populations, and these areas were used to guide discussions among the working group as alternative management actions were crafted.

Table 5. Predicted km^2 of suitable habitat that will be occupied by mountain goat populations in 50 years under alternative predictive models and different management alternatives. Model predictions are from the top non-climate-related Resource Selection Function (RSF) model, representing the hypothesis that climate change will not limit the distribution of mountain goat populations, and the top climate-related RSF model combined with mid-century (2040-2069) spatial forecasts from 3 divergent Global Climate Models (GCMs), representing the hypothesis that climate change will impact the distribution of mountain goat populations and capturing uncertainty in future climate projections. Model weights were elicited from the working group, and the model weight for the top climate-related RSF model was split equally among the 3 GCM forecasts. Expected values are weighted means (using the model weights) of individual model predictions.

Model	Model Weight	Status Quo strategy	Top-down mortality manage-ment strategy	Intro-duction strategy	Augment-ation strategy	Habitat protecti on strategy	Combined strategy, with augment-ations	Combined strategy, no augment-ations
Non-climate-related RSF	0.389	17,283	17,283	19,456	17,283	17,283	19,421	19,421
Climate-related RSF, CanESM2 GCM	0.204	15,259	15,259	15,699	15,259	15,259	15,629	15,629
Climate-related RSF, IPSL-CM5A-MR GCM	0.204	13,734	13,734	14,072	13,734	13,734	14,054	14,054
Climate-related RSF, CCSM4 GCM	0.204	14,713	14,713	15,121	14,713	14,713	15,035	15,035
Expected Value (weighted mean)		15,624	15,624	16,711	15,624	15,624	16,662	16,662

Predictions of the number of mountain goat population units meeting population trend objectives one generation from the present

Limited data exist on mountain goat population dynamics, so there is considerable uncertainty about future population dynamics and the effects of management. We developed a predictive population modeling procedure that incorporated uncertainty in starting population sizes, vital rates, starting population age structures, and the age structure of mountain goats harvested by hunters. Population projection simulations incorporating these sources of uncertainty were coded in the R statistical software, using both the popbio and rramas packages. Simulations were constructed to include the 58 current mountain goat population units in addition to any new populations introduced during hypothetical management alternatives. Simulations were run for 9 time steps (representing the mean mountain goat generation time in years; Festa-Bianchet and Côté 2008), and 1000 stochastic simulations were completed for each hypothetical alternative management action.

Smith and DeCesare (2017) summarized the most recent aerial count data for mountain goat populations across Montana. Because of the limited quality and extent of many aerial surveys for mountain goats, they also queried biologists for each herd regarding population estimates and their range of confidence in those estimates (Smith and DeCesare 2017; Appendix 1 Question 1). We sampled starting population sizes by treating the “Range of Confidence” values provided by biologists as 95% confidence intervals, centered around their best point estimates, to randomly draw a starting population size for each stochastic iteration. We used the 2010-present trend estimates provided by biologists for each mountain goat population unit to prescribe the population trend used for stochastic simulations in each population (Smith and DeCesare 2017; Appendix 1 Question 6).

Extensive vital rate data do not exist for mountain goats in Montana, so we relied on vital rate data from Alberta and Alaska, the only two areas where long-term studies of mountain goat population dynamics have been conducted. Following Hamel et al. (2006) and Côté and Hamel (2018), we built a 2-sex, 17-stage (age-based), post-birth Leslie matrix population model (Caswell 2001), with the youngest age class representing newborns, to simulate uncertainty in mountain goat vital rates (Figure 10). Vital rates estimated from mountain goats in Alberta were divided into 3 trend scenarios representing population dynamics of mountain goat populations during different time periods. This included periods when the population was declining (2004–2017), stable (1993–2017, with slight upward adjustments to vital rates so asymptotic lambda=1.000), and increasing (1993–2003). We used vital rate values and their variances from each of these 3 study periods to model Montana populations deemed to be declining, stable, or increasing according to the biologist trend estimates. To represent vital rates for Montana mountain goat populations with uncertain trends based on the professional

	0f	0m	1f	1m	2f	2m	3f	3m	4f	4m	5f	5m	6f	6m	7f	7m	8f	8m	9f	9m
0f	·	·	·	·	F_3S_{sf}	·	F_4S_{sf}	·	F_aS_{af}	·	F_aS_{af}	·	F_aS_{af}	·	F_aS_{af}	·	F_aS_{af}	·	F_oS_{af}	·
0m	·	·	·	·	F_3S_{sf}	·	F_4S_{sf}	·	F_aS_{af}	·	F_aS_{af}	·	F_aS_{af}	·	F_aS_{af}	·	F_aS_{af}	·	F_oS_{af}	·
1f	S_0	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
1m	·	S_0	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
2f	·	·	S_1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
2m	·	·	·	S_1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
3f	·	·	·	·	S_{sf}	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
3m	·	·	·	·	·	S_{sm}	·	·	·	·	·	·	·	·	·	·	·	·	·	·
4f	·	·	·	·	·	·	S_{sf}	·	·	·	·	·	·	·	·	·	·	·	·	·
4m	·	·	·	·	·	·	·	S_{sm}	·	·	·	·	·	·	·	·	·	·	·	·
5f	·	·	·	·	·	·	·	·	S_{sf}	·	·	·	·	·	·	·	·	·	·	·
5m	·	·	·	·	·	·	·	·	·	S_{sm}	·	·	·	·	·	·	·	·	·	·
6f	·	·	·	·	·	·	·	·	·	·	S_{af}	·	·	·	·	·	·	·	·	·
6m	·	·	·	·	·	·	·	·	·	·	·	S_{am}	·	·	·	·	·	·	·	·
7f	·	·	·	·	·	·	·	·	·	·	·	·	S_{af}	·	·	·	·	·	·	·
7m	·	·	·	·	·	·	·	·	·	·	·	·	·	S_{am}	·	·	·	·	·	·
8f	·	·	·	·	·	·	·	·	·	·	·	·	·	·	S_{af}	·	·	·	·	·
8m	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	S_{am}	·	·	·	·

Figure 10. A portion of the Leslie matrix population model used to simulate population dynamics of mountain goats in Montana. Survival (S) from each successive age-sex class is displayed along the diagonal. The production of newborns, the product of fecundity (F) of each female age class and their survival (S) to the end of the time step, is shown in the first two rows. Vital rates differed for newborns, yearlings, subadults, and adults. The full Leslie matrix model has 34 stages accounting for females, males, and 17 ages, 0 (newborns) through 16 years old.

judgment of biologists, we created an uncertain category for vital rates with mean vital rates equivalent to those from a stable population but larger confidence intervals that fully spanned the range of values from all study periods, including declining to increasing values (Table 6).

We conducted simulations as random draws of adult female survival, adult female fecundity, and kid survival (Table 6), and we derived the remaining vital rates to populate the Leslie matrix population model as proportions of these vital rates. Yearling survival was assumed to be 91% of adult female survival, which was derived as the average proportionate difference between yearling female and adult female survival in the Alberta study (Côté and Hamel 2018).

Table 6. Vital rate scenarios (mean and 95% Confidence Intervals) for adult females and newborns used to represent declining, stable, increasing, and uncertain population trends in the Leslie matrix population model for mountain goats in Montana. These vital rates were taken or derived from the Caw Ridge population in Alberta, one of the only long-term studies of mountain goat population dynamics ever undertaken (Hamel et al. 2006, Côté and Hamel 2018).

	Adult female survival		Newborn survival		Adult female fecundity	
	Mean	95% CI	Mean	95% CI	Mean	95% CI
Declining	0.87	(0.85,0.90)	0.48	(0.39,0.56)	0.38	(0.30,0.46)
Stable	0.92	(0.89,0.95)	0.59	(0.48,0.70)	0.67	(0.58,0.76)
Increasing	0.94	(0.90,0.99)	0.62	(0.49,0.75)	0.75	(0.65,0.85)
Uncertain	0.92	(0.85,0.99)	0.59	(0.39,0.75)	0.67	(0.30,0.85)

Subadult female survival and subadult male survival were derived as 104% and 97% of the adult female survival rate, respectively, representing the mean of the 1993-2017 period in Alberta (Côté and Hamel 2018) and the moderate climate scenario projections of mountain goat population dynamics in southeastern Alaska (White et al. 2018). Adult male survival, older female (>8 years) survival, and older male (>8 years) survival were derived as 93%, 84%, and 74% of the adult female survival rate, respectively, also representing the mean of the 1993-2017 data in Alberta (Côté and Hamel 2018) and the moderate climate scenario projections of mountain goat population dynamics in southeastern Alaska (White et al. 2018). Fecundity for 3-year-old females set to 0.04, and fecundity for 4-year-old females was derived as 63% of adult fecundity, representing intermediate values from those observed in Alberta (Hamel et al. 2006, Festa-Bianchet and Côté 2008, Côté and Hamel 2018) and Alaska (White et al. 2018). Finally, older female (>8 years) fecundity was derived as 94% of adult female fecundity, which is the mean of values observed during the 1993-2017 period in Alberta (Côté and Hamel 2018) and the moderate climate scenario projections of mountain goat population dynamics in southeastern Alaska (White et al. 2018).

During each simulation iteration, we drew values from a beta distribution that treated variation in each of the 3 key vital rates and population trend scenarios being simulated (Table 6) as approximately normal but bounded by 0 and 1, and the other vital rates were adjusted accordingly. We estimated a stable age distribution for the population matrix representing a stable population, and then for each simulation iteration we randomly sampled from that age distribution to establish the various counts of goats in each sex and age class, summing to the total starting population size drawn from the distribution for each population.

To simulate the effects of mountain goat harvest on population dynamics, we used 2019 mountain goat hunting license quotas for hunting districts with open seasons, multiplied by a 72% average hunter success rate (2000-2015), and rounded up to the nearest integer to set harvest for the status quo strategy. These harvest quotas were adjusted accordingly for the other management strategies considered. We included variation in the age and sex structure of the harvested animals using the Montana database of >2,500 harvested mountain goats during 2000–2015 (Table 7). Each mountain goat harvest was drawn randomly from this distribution during simulations.

Table 7. Age structure of mountain goats harvested in Montana during 2000-2015, from Montana harvest databases and Smith and DeCesare (2017).

Age bracket	Males	Females
0 to 3	23%	10%
4 to 6	28%	15%
7 to 10	12%	8%
>10	2%	3%
Total	65%	35%

In simulations for the top-down mortality management strategy, we removed all harvest from simulations of mountain goat populations not currently meeting or exceeding their trend objectives. We assumed the effect of increased harvest of carnivores would be an increase in kid survival, which is the primary vital rate impacted by carnivores during the long-term mountain goat population study in Alberta (Festa-Bianchet et al. 1994, Kirby Smith personal communication). For simulations under the top-down mortality management strategy, we therefore increased kid survival from the rate dictated by the current population trend to the "increasing" mean and variance values of kid survival for all populations not meeting or exceeding trend objectives, where increased harvest of large carnivores would be implemented.

In simulations of strategies involving mountain goat translocations (the *Introduction*, *Augmentation*, *Combined Strategies- with and without augmentations*), we increased starting population size in the recipient herds and decreased starting population size in the source herds when translocations were sourced from herds within Montana. In all cases when animals were translocated for introduction or augmentation, we changed the vital rate package for the recipient population to the uncertain package, centered around a stable population trend but with the largest amount of uncertainty. For any populations treated as source populations for translocations, we subtracted the full number of translocated animals from the initial population size and set harvest quotas to 0 for one mountain goat generation (9 years), thereby replacing harvest mortality with translocation removals in source populations.

Studies of small populations of woodland caribou in Canada have indicated weak evidence of Allee effects (positive density dependence) in adult survival (Witmer et al. 2005, McLellan et al.

2010), which could indicate that survival will increase as mountain goat populations initially increase from small numbers due to translocations (*sensu* DeCesare et al. 2011). While this may be a reasonable hypothesis for how translocation could improve the outlook for small populations of mountain goats, additional uncertainties also exist surrounding translocation, including the potential for reduced fidelity or survival of transplanted mountain goats immediately post-translocation. For example, in 1989, 13 mountain goats from Olympic National Park were released near Red Mountain, just southeast of the Scapegoat Wilderness Area in western Montana. A year after the release, only one of these released mountain goats was known to remain near the release site, and several wandered up to a hundred miles away and were killed in other areas. Rather than build in these complexities, we used the uncertain vital rate package to increase the uncertainty around dynamics of such herds, assuming stable mean vital rates.

Similarly, for simulations involving habitat protection, we assumed such protections would manifest demographically in the form of increased fecundity of adult females. Hamel et al. (2010) showed that female reproduction during a given year is sensitive to the costs faced during the year prior, such as prior reproductive effort or high population density. While an effect of disturbance on fecundity hasn't been empirically shown, we assumed this was the most likely pathway between such a management action and a demographic outcome. Thus, herds assigned habitat protection under a given alternative were assigned the fecundity values from the increasing trend scenario (Table 6).

Uncertainty surrounding starting population sizes, vital rates, starting population age structures, and the age structure of mountain goats harvested by hunters was incorporated into each simulation iteration in each time step for each population. This resulted in a wide range of projections for each population during each simulation over the period of one mountain goat generation. The final population size for each simulation was used to assess whether each population was increasing (≥20% higher than present population), decreasing (≥20% lower than present population), or stable (<20% higher or lower than present population). To represent the variability in simulation results in decision analysis, we weighted the distribution of simulated values for each population approximately normally. We placed a weight of 0.45 on the median simulated values, a weight of 0.25 on the lower and upper quartiles of the simulated values, and a weight of 0.025 on the lower and upper 2.5% of simulated values for each population. We calculated an expected value prediction for the number of mountain goat herd units achieving population trend objectives one generation from the present under each alternative as the weighted mean of this distribution (Table 8).

Table 8. Predictions of the number of mountain goat population units that will meet population trend objectives one generation from the present. Model weights were selected to represent an approximately normal distribution of the population simulation model predictions for each mountain goat population unit. Expected values are weighted means (using the model weights) of the distribution of population simulation model predictions.

Model	Model Weight	Status Quo strategy	Top-down mortality manage-ment strategy	Intro-duction strategy	Augment-ation strategy	Habitat protection strategy	Combined strategy, with augment-ations	Combined strategy, no augment-ations
Lower 0.025 of simulated values	0.025	2	2	7	6	2	6	5
Lower 0.25 of simulated values	0.25	9	11	13	19	11	19	12
Median simulated value	0.45	15	17	20	26	15	26	17
Upper 0.75 of simulated values	0.25	26	35	28	36	27	36	32
Upper 0.975 of simulated values	0.025	46	53	50	48	47	55	54
Expected Value (weighted mean)		16.7	20.5	20.7	26.8	17.5	27.0	20.1

Predictions of the bighorn sheep disease risk value function

Montana currently has 29 mountain goat herd units that occupy ranges overlapping bighorn sheep herds. Only 2 mountain goat herds in Montana have been evaluated for their respiratory pathogen communities using a statistically-robust sample size; both herds were found to carry pneumonia-associated pathogens, and 1 of these herds currently occupies a range overlapping a bighorn sheep herd (Almberg et al. 2016, Almberg et al. 2018). Both herds, as well as other mountain goat herds from outside of Montana that are known to harbor pneumonia-associated pathogens, would be involved in translocations under some of the management alternatives being considered in this SDM process.

The working group used three hypotheses to capture the considerable uncertainty about the number of bighorn sheep herds overlapping mountain goat herds with pneumonia-associated pathogens. The first two hypotheses bracketed the spectrum of possibilities. The first states that the mountain goat herds currently known to carry pneumonia-associated pathogens are the only such cases in Montana. The second states that all mountain goat herds in Montana carry pneumonia-associated pathogens. The third hypothesis is ostensibly more nuanced. The large-scale decline in bighorn sheep populations during Spanish colonization and through westward expansion of the United States may be due to pneumonia-associated pathogens introduced by domestic sheep (Cassirer et al. 2018). The third hypothesis therefore states that the mountain goat herds with pneumonia-associated pathogens are those that can be historically traced to range overlap with domestic sheep herds, via direct overlap or translocations of mountain goat or bighorn sheep with ranges that overlapped domestic sheep. Historical records of mountain goat ranges, mountain goat transplants, and bighorn sheep transplants (Picton and Lonner 2008) were combined with the working group's knowledge of the historical distribution of domestic sheep grazing areas to evaluate this third hypothesis. While this hypothesis represents a more nuanced biological concept, all 29 mountain goat herds currently overlapping bighorn sheep herds and all the mountain goat herds that would be sources for the translocations considered by the working group can be historically traced to range overlap with domestic sheep. In a practical sense, the second and third hypotheses are therefore identical in terms of predicting the number of bighorn sheep herds that overlap mountain goat herds with pneumonia-associated pathogens.

We elicited belief weights in the 3 models (hypotheses) of the number of bighorn sheep herds overlapping mountain goat herds with pneumonia-associated pathogens using a likelihood point method. Working group members distributed 100 points according to their personal belief that each model most closely represented truth. The points allocated to each model were divided by 100 to obtain a relative probability weight for each model for each working group participant, and these values summed to 1 for each participant. We used a modified Delphi method for this elicitation (Clark et al. 2006). After completing the exercise, participants were shown individual and group results, discussed differing probability weights and their rationale, and were given the opportunity to change their values. The working group mean probability weight for each model was then used to represent the working group belief weight in each model. The working group assigned a weight of 0.04 to the model indicating that mountain goat herds currently known to harbor pneumonia-associated pathogens are the only such herds, a weight of 0.50 to the model indicating that all mountain goat herds in Montana carry pneumonia-associated pathogens, and a weight of 0.46 to the model indicating that mountain goat herds with a historical tie to range overlap with domestic sheep carry pneumonia-associated pathogens (Table 9).

Table 9. Bighorn sheep disease risk value function accounting for both the predicted number of bighorn sheep herds overlapping mountain goat herds with pneumonia-associated pathogens under 3 alternative hypotheses (values in italics) and risk tolerance for mixing mountain goat and bighorn sheep herds during translocations. The working group mean microbial mixing risk multiplier of 1.6 was used to calculate the risk value function. Model weights were elicited from the working group. Expected values are weighted means (using the model weights) of individual model predictions.

Model	Model Weight	Status Quo strategy	Top-down mortality manage-ment strategy	Intro-duction strategy	Augment-ation strategy	Habitat protection strategy	Combined strategy, with augment-ations	Combined strategy, no augment-ations
Only mountain goat herds currently known to have pneumonia pathogens have them	0.04	*1*	*1*	*2*	*5*	*1*	*7*	*2*
All mountain goat herds have pneumonia pathogens	0.50	*29*	*29*	*31*	*29*	*29*	*31*	*31*
Mountain goat herds with a historical tie to range overlap with domestic sheep have pneumonia pathogens	0.46	*29*	*29*	*31*	*29*	*29*	*31*	*31*
Expected Value (weighted mean)		*27.8*	*27.8*	*29.8*	*28.0*	*27.8*	*30.0*	*29.8*
Number of bighorn sheep herds being mixed with mountain goat herds		0	0	2	8	0	8	2
Model-weighted risk value function		27.8	27.8	33.0	40.7	27.8	42.7	33.0

In addition to the disease risk stemming from the presence of pneumonia pathogens, the working group was concerned with risk stemming from mixing the microbial communities living in transplanted mountain goats with those living in resident mountain goats or bighorn sheep. Risk tolerance for mixing microbial communities during translocations was accounted for by eliciting a risk multiplier from the working group. This value was elicited by asking working group members the question "Relative to the die-off risk associated with pneumonia-associated pathogens being present in a specific bighorn sheep or mountain goat herd, I would rate pneumonia die-off risk associated with transplanting new mountain goats into the area as ____." FWP Wildlife Health Program staff with expertise in disease ecology and veterinary science were also asked and responded to this question. Respondents were provided with the meaning of risk multiplier values of 0, 0.5, 1, 1.5, 2, and >2 as references to aid in determining their personal choice for a risk multiplier value.

The elicitation was conducted using a modified Delphi method (Clark et al. 2006). After independently determining their personal value for the risk multiplier, participants were shown individual and group results, discussed differing values and their rationale, and were given the opportunity to change their values. This process resulted in a range of risk multiplier values of 0-3 among the group, all of which were based on logic and personal values. The 0 value reflected that many mountain goat herd units have struggling populations. While mixing microbial communities during translocations may perpetuate these struggles, translocations could possibly improve the population trend for these populations, so translocations are worth the risk. The 3 value reflected that rigorous evidence is limited for translocations improving mountain goat herd demography, and mixing microbial communities may perpetuate poor demography by causing disease, so translocations are not worth the risk. The group mean microbial mixing risk multiplier value of 1.6 was used to calculate the risk value function accounting for both the number of bighorn sheep herds overlapping mountain goat herds with pneumonia-associated pathogens and risk tolerance for mixing mountain goat and bighorn sheep herds during translocations (Table 9). The full range of microbial mixing risk multiplier values was also retained for analyzing the sensitivity of the optimal decision to these values.

<u>Predictions of the mountain goat disease risk value function</u>

Montana currently has 58 total mountain goat herd units, 2 of which have been directly evaluated and were found to carry pneumonia-associated pathogens (Almberg et al. 2016, Almberg et al. 2018). More extensive testing of bighorn sheep herds has occurred across Montana, and most bighorn sheep herds evaluated have pneumonia-associated pathogens (Almberg et al. 2019, Appendix 2). A total of 22 additional, currently occupied mountain goat herd units have ranges overlapping bighorn sheep herds with pneumonia associated pathogens. Therefore, a minimum of 24 mountain goat herd units currently either carry or are exposed to pneumonia-associated pathogens due to range overlap with bighorn sheep. Many of these herds, as well as other mountain goat herds from outside of Montana that are known to harbor pneumonia-associated pathogens, would be involved in translocations under the management alternatives being considered in this process.

The same 3 models (hypotheses) and model weights were used to represent uncertainty in the total number of mountain goat herds exposed to pneumonia-associated pathogens. Based on historical transplant records (Picton and Lonner 2008) and knowledge of historical domestic sheep grazing areas, 2 mountain goat herd units (the West Cabinets and Great Burn herds) could not be traced to historical range overlap with domestic sheep. This created a small difference between the 2nd (that all mountain goat herds have pneumonia-associated pathogens) and 3rd (mountain goat herds with a historical tie to range overlap with bighorn sheep have exposure to pneumonia-associated pathogens) hypotheses. The working group mean microbial mixing risk multiplier value of 1.6 was used to calculate the risk value function (Table 10).

Predicting costs

We predicted only operational costs and not personnel costs of implementing alternative management actions. Personnel costs are specific to the logistics of implementing management actions and dependent on annual work task assignments to staff with different salaries, neither of which could be defined within the time frame of this process for the alternatives we considered. We considered base operational costs, common to all alternatives, to consist of annual population and disease survey programs. To predict annual mountain goat population survey costs, we used records from the FWP Wildlife Information System to determine that FWP staff spent an average of 38 helicopter hours and 7 fixed-wing hours surveying mountain goat herds per year during the previous 10 years, for a mean annual expenditure of approximately $23,000 using current aircraft hourly rates. Additionally, the bighorn sheep and mountain goat pathogen testing program consists of aerial captures of a statistically robust sample of mountain goats from a target of at least 1 herd per year since 2016, resulting in an annual cost of approximately $23,000. Total annual base costs were therefore predicted as $46,000 for each alternative. We added an annual cost of $10,000 to create additional signage and maps for the habitat protection alternative.

Table 10. Mountain goat disease risk value function accounting for both the predicted number of mountain goat herds with or exposed to pneumonia-associated pathogens under 3 alternative hypotheses (values in italics) and risk tolerance for mixing mountain goat and bighorn sheep herds during translocations. The working group mean microbial mixing risk multiplier of 1.6 was used to calculate the risk value function. Model weights were elicited from the working group. Expected values are weighted means (using the model weights) of individual model predictions.

Model	Model Weight	Status Quo strategy	Top-down mortality manage-ment strategy	Intro-duction strategy	Augment-ation strategy	Habitat protection strategy	Combined strategy, with augment-ations	Combined strategy, no augment-ations
Only mountain goat herds currently known to have pneumonia pathogens have them	0.04	*24*	*24*	*26*	*29*	*24*	*30*	*26*
All mountain goat herds have pneumonia pathogens	0.50	*58*	*58*	*63*	*58*	*58*	*61*	*61*
Mountain goat herds with a historical tie to range overlap with domestic sheep have pneumonia pathogens	0.46	*56*	*56*	*60*	*56*	*56*	*59*	*59*
Expected Value (weighted mean)		*55.7*	*55.7*	*60.1*	*55.9*	*55.7*	*58.8*	*58.6*
Number of mountain goat and bighorn sheep herds being mixed		0	0	2	10	0	13	3
Model-weighted risk value function		55.7	55.7	63.3	71.8	55.7	79.5	63.4

Alternatives involving mountain goat translocations would incur additional operational costs associated with capturing, moving, and releasing mountain goats. To predict these costs, we used the recent per-mountain-goat capture and pathogen testing costs of $1500 accrued during mountain goat health sampling captures. Additionally, FWP records indicate that an additional $500 has been spent on average, per translocation event, during recent bighorn sheep transplant operations. These per-mountain-goat and per-translocation-event costs were added to alternatives involving translocations using the mean per-translocation costs for each alternative, therefore assuming a single mountain goat translocation event would occur annually. This assumption induced a time mismatch between our cost predictions and predictions for the population- and disease-related fundamental objectives because not all the translocations would be implemented immediately as was assumed in those predictions. However, implementing a single translocation event per year is more realistic, and the slight timing mismatch should not confound general conclusions from the overall decision analysis. Including translocation costs resulted in vastly different annual costs for the alternatives considered (Table 11).

Table 11. Predicted annual costs for each alternative.

	Status Quo strategy	Top-down mortality manage-ment strategy	Intro-duction strategy	Augment-ation strategy	Habitat protection strategy	Combined strategy, with augment-ations	Combined strategy, no augment-ations
Predicted annual costs	$46,000	$46,000	$121,500	$179,833	$56,000	$162,973	$131,500

Predicting the extent of social conflict created by mountain goat management actions

No quantitative data were available for predicting the amount of social conflict that would be created by each alternative, so working group participants used their professional judgement and experience to predict this metric on a constructed scale of 1-5, representing no, low, medium, high, and extreme levels of social conflict. The working group was instructed to consider possible negative impacts on other societal values associated with increased carnivore hunting, limits to extractive industries, limits to non-motorized recreation (e.g., skiing, hunting, biking, camping), limits to motorized recreation (e.g., motorized roads, snow machines), real and perceived disease spillover issues with domestic livestock, and limits to commercial use (e.g., tours, outfitters). Predictions among working group participants differed little, though the overall mean predictions from the working group differed among alternatives (Table 12). The

Status quo strategy is predicted to maintain the current, low levels of social conflict associated with mountain goat management. The *Top-down mortality management strategy* is predicted to generate higher levels of social conflict due to increased carnivore hunting. Similarly, the *Habitat protection strategy* is predicted to generate higher levels of social conflict due to limits being placed on human activities and access to public lands. The *Introduction strategy* and *Augmentation strategy* are predicted to generate smaller increases in social conflict above the *Status quo strategy*, largely due to overlap of some proposed translocations with domestic sheep in areas where social conflict already exists. For example, the *Introduction strategy* describes a possible mountain goat introduction into the Gravelly Mountains, where there is an ongoing federal lawsuit over domestic sheep and bighorn sheep management. The *Combined strategy, with augmentations* is predicted to generate the most social conflict, as it contains elements of each of the other strategies. The same predictions were used for the *Combined strategy, with augmentations* and the *Combined strategy, without augmentations* because the only difference was in the exclusion of augmentations in the latter, which did not affect these predictions.

Table 12. Predicted amount of social conflict that would be created by each alternative, on a categorical scale of 1-5 (none, low, medium, high, and extreme). Values represent mean predictions from the working group.

	Status Quo strategy	Top-down mortality manage-ment strategy	Intro-duction strategy	Augment-ation strategy	Habitat protection strategy	Combined strategy, with augment-ations	Combined strategy, no augment-ations
Predicted level of social conflict	1.64	3.55	2.82	2.18	4.05	4.13	4.13

Decision analysis, tradeoffs, and optimization

Given the fundamental objectives, management alternatives, and predicted consequences, we structured our decision analysis to establish priority information needs and recommend management actions for mountain goat management in Montana. We identified priority information needs using value of information and sensitivity analyses to elucidate when additional information would affect the choice of management alternatives and thereby be directly relevant to improving mountain goat management. We used these analyses combined with quantitative methods to evaluate multiple-objective decisions to identify management recommendations.

Value of Information

The value of information concept represents the difference between the value of expected management outcome when a decision is made now, based on existing and incomplete information, versus the value of the management outcome were new information to be gained that clears up the current uncertainty (Canessa et al. 2015). Considerable uncertainty surrounds predictions for objectives 1, 2, 3, and 4 (Table 5, Table 8, Table 9, Table 10). To determine the relevance of uncertainty in predictions for each of these objectives to management recommendations, we used Expected Value of Perfect Information (EVPI) analysis (Canessa et al. 2015, Bolam et al. 2019) separately for each fundamental objective that incorporated uncertainty. The EVPI is the expected benefit of eliminating uncertainty entirely. While entirely eliminating uncertainty is not realistic, EVPI can provide insight into the relative importance of reducing different types of uncertainty. Because our predictive models incorporating uncertainty were very general and required many assumptions due to the lack of mountain goat field data from Montana, we did not place emphasis on the exact value of EVPI calculations. Instead, we used EVPI>0 as a threshold to identify priority information needs.

Uncertainty about the effect of climate change on the future distribution of mountain goat herds, combined with uncertainty about how climate change impacts will occur spatially under different GCMs, has a large effect on the predicted area that will be occupied by mountain goat herds in 50 years in Montana (Table 5). Mountain goat populations could occupy up to 38%, >5300 km^2, more area under the model assuming climate change will not impact the distribution of mountain goat populations, compared to the model assuming that climate change will impact the distribution of mountain goat populations under the IPSL-CM5A-MR GCM (Table 5). However, EVPI=0 for the predicted km^2 of suitable habitat that will be occupied by mountain goat populations in 50 years. This is because alternatives that involve new introductions of mountain goat populations are predicted to result in more suitable area occupied by mountain goats in 50 years under every model we considered (Table 5). Regardless of the model one believes or uses, the *Introduction* strategy is always predicted to result in more area occupied than other alternatives, followed by the *Combined strategies- with and without augmentations*. We therefore do not expect that resolving this uncertainty will result in more area occupied by mountain goat populations in 50 years.

Uncertainty about mountain goat population demography and population dynamics has a large effect on the predicted number of mountain goat populations that will meet trend objectives in one generation (Table 8). Our predictions range from 2 (3% of the current number of mountain goat population units) to 55 (95% of the current number of mountain goat population units) mountain goat populations in Montana meeting population trend objectives one generation from the present, considering the uncertainty, modeling assumptions, and management alternatives we included. We estimate that EVPI=0.02 for the number of mountain goat populations that will meet trend objectives in one generation. This means that the optimal management alterative choice is affected by the lack of information on mountain goat demography and population dynamics, and that more information about mountain goat demography and population dynamics would increase the number of mountain goat populations meeting trend objectives one generation from the present.

Uncertainty about pneumonia pathogens and risk of mixing pathogens among herds during translocations has a large effect on the bighorn sheep disease risk value function (Table 9). We predict that somewhere between 3-100% of current bighorn sheep herds overlapping mountain goat herd units will be exposed to mountain goat populations with pneumonia-associated pathogens under the models and alternatives we considered (Table 9). We estimated that EVPI=0 for the full range of alternatives we considered, because alternatives that do not involve translocations of mountain goats result in fewer bighorn sheep herds exposed to mountain goat populations with pneumonia-associated pathogens, under every model we considered (Table 9). However, there is a long history of mountain goat translocations in Montana (Picton and Lonner 2008), and translocations may be a part of future mountain goat conservation efforts. When limited to considering only the alternatives with translocations, EVPI=0.13 for the number of bighorn sheep herds exposed to mountain goats with pneumonia-associated pathogens. This means that efforts to increase information about which bighorn sheep herds are exposed to pneumonia-associated pathogens from mountain goats will affect the optimal decision for minimizing disease risks to bighorn sheep when mountain goats are transplanted.

Interestingly, incorporating the microbial mixing risk multiplier into EVPI calculations for the bighorn sheep disease risk value function decreased the EVPI for alternatives with translocations to 0. This is because accounting for the decreased risk tolerance for mixing microbial communities results in alternatives with new introductions outperforming alternatives with augmentations in every model we considered. This result is partially an artifact of the specific alternatives that we evaluated, combined with how the microbial mixing risk multiplier was incorporated as a multiplier on the number of herds being mixed. The 2 alternatives involving new introductions and 2 alternatives involving augmentations each resulted in 2 and 8 bighorn sheep herds being mixed with mountain goat herds, respectively. If the number of bighorn sheep herds being mixed with mountain goat herds were different among alternatives, we would see EVPI>0 when accounting for risk intolerance for mixing microbial communities in alternatives involving translocations.

Uncertainty about pneumonia pathogens and risk of mixing pathogens among herds during translocations also has a large effect on the mountain goat disease risk value function (Table 10). We predict that somewhere between 41-100% of current mountain goat herds harbor pneumonia-associated pathogens or will be exposed to bighorn sheep populations with pneumonia-associated pathogens under the models and alternatives we considered (Table 10). We estimated that EVPI=0 for the full range of alternatives we considered, because alternatives that do not involve translocations of mountain goats result in fewer herds harboring or being exposed to pneumonia-associated pathogens, under every model we considered (Table 10). When limited to considering only the alternatives with translocations, EVPI=0.13 for the number of mountain goat herds harboring or exposed to bighorn sheep with pneumonia-associated pathogens. This means that efforts to increase information about which mountain goat and bighorn sheep herds harbor pneumonia-associated pathogens will affect the optimal decision about which mountain goat herds and new population areas should be involved in translocations. For the mountain goat disease risk value function, incorporating the microbial mixing risk multiplier into EVPI calculations increased the EVPI to 0.20. This is because the alternatives involving translocations we considered each involved differing numbers of mountain goat and bighorn sheep herds being mixed together (Table 10). Incorporating risk intolerance for mixing microbial communities thus amplified the value of information about which mountain goat and bighorn sheep herds harbor pneumonia-associated pathogens for improving decisions to minimize disease risks to mountain goats when they are transplanted.

Multiple objective decision analysis and sensitivity analysis

To consider tradeoffs and determine the relative performance of each alternative at achieving the full set of fundamental objectives requires a value preference scale to represent the relative importance of achieving each fundamental objective (Keeney 1992). We used swing-weighting to derive weights for each fundamental objective (Conroy and Peterson 2013). Swing weights account for both the relative importance placed on each fundamental objective and the difference in the degree to which each fundamental objective will be achieved from the worst to the best alternative (i.e., the “swing”). To derive swing weights, we first created a consequence table using the expected value predictions for each fundamental objective (Table 13). Working group members each completed a swing weighting exercise using these expected values. Following the weighting exercise, working group members were shown overall results and discussed the rationale for their individual swing weights, revealing substantial variation. We used the mean swing weights for each fundamental objective to represent the working group consensus in multiple objective decision analysis. Individual weighting schemes varied largely in the relative weight placed on achieving distribution and population objectives versus disease risk objectives. We retained 2 example weighting schemes that we termed “recovery focused” and “risk averse” to represent the individual variation in weighting schemes for use in sensitivity analyses (Table 14).

Table 13. Consequence predictions for each fundamental objective and each alternative. For consequence predictions that incorporated uncertainty represented by multiple models, expected value predictions are shown.

Fundamental objective	Measurable Attribute	Status Quo strategy	Top-down mortality manage-ment strategy	Intro-duction strategy	Augment-ation strategy	Habitat protection strategy	Combined strategy, with augment-ations	Combined strategy, no augment-ations
Maximize the number of occupied mountain goat population units.	km^2 of suitable habitat that is occupied in 50 years	15,624	15,624	16,711	15,624	15,624	16,662	16,662
Maximize the number of mountain goat population units meeting objectives statewide, considering limitations in each unit.	# goat population units meeting trend objectives, one generation from present	16.70	20.53	20.68	26.80	17.48	26.98	20.13
Minimize disease risks to bighorn sheep.	Bighorn sheep risk value function	27.83	27.83	32.97	40.73	27.83	42.73	32.97
Minimize disease risks to mountain goats.	Mountain goat risk value function	55.67	55.67	63.27	71.78	55.67	79.47	63.40
Minimize cost.	Annual cost ($)	$46,000	$46,000	$121,500	$179,833	$56,000	$162,973	$131,500
Minimize social conflict resulting from goat management.	constructed 1-5 scale	1.64	3.55	2.82	2.18	4.05	4.13	4.13

Table 14. Swing weights for each fundamental objective elicited from working group members. Group mean weights were used for multiple objective decision analysis. Recovery focused and risk averse weights were retained as examples to examine the sensitivity of the optimal alternative to the weighting scheme.

Fundamental objective	Group mean weights	Recovery focused weights	Risk averse weights
Maximize the number of occupied mountain goat population units.	0.19	0.25	0.03
Maximize the number of mountain goat population units meeting objectives statewide, considering limitations in each unit.	0.27	0.36	0.18
Minimize disease risks to bighorn sheep.	0.19	0.07	0.26
Minimize disease risks to mountain goats.	0.20	0.07	0.26
Minimize cost.	0.06	0.11	0.13
Minimize social conflict resulting from goat management.	0.09	0.14	0.13

We used the Simple, Multi-Attribute Rating Technique (SMART) to analyze the degree to which each alternative would achieve the full set of fundamental objectives (Goodwin and Wright 2001). Because each fundamental objective was measured on a different scale, predictions were first normalized onto a 0-1 scale, with 0 representing the worst predicted value and 1 representing the best predicted value for each fundamental objective. Each normalized prediction was then multiplied by the group mean swing weights to account for the variable importance and swing in predictions for each objective. The resulting values are directly comparable to one another in a relative sense, and summing them for each alternative generates the overall weight of support for that alternative. This SMART analysis identified the *Introduction strategy* as the optimal approach, with substantial support also found for the *Combined strategy, without augmentations*, the *Top-down mortality management strategy*, and the *Status quo strategy* (Table 15). There was also substantial variation in the degree to which each alternative would meet each fundamental objective.

Table 15. Normalized, weighted consequence predictions for each fundamental objective and each alternative from the Simple, Multi-Attribute Rating Technique (SMART) analysis. The working group mean swing weights were used in this SMART analysis.

Fundamental objective	Status Quo strategy	Top-down mortality manage-ment strategy	Intro-duction strategy	Augment-ation strategy	Habitat protection strategy	Combined strategy, with augment-ations	Combined strategy, no augment-ations
Maximize the number of occupied mountain goat population units.	0.00	0.00	0.19	0.00	0.00	0.18	0.18
Maximize the number of mountain goat population units meeting objectives statewide, considering limitations in each unit.	0.00	0.10	0.11	0.27	0.02	0.27	0.09
Minimize disease risks to bighorn sheep.	0.19	0.19	0.12	0.03	0.19	0.00	0.12
Minimize disease risks to mountain goats.	0.20	0.20	0.14	0.07	0.20	0.00	0.14
Minimize cost.	0.06	0.06	0.02	0.00	0.05	0.01	0.02
Minimize social conflict resulting from goat management.	0.09	0.02	0.05	0.07	0.00	0.00	0.00
Weight of support (sum)	0.54	0.57	0.63	0.43	0.46	0.46	0.55

The weight of support for each alternative was sensitive to the swing weighting scheme (Figure 11). Compared to SMART analysis using the group mean swing weights, using the recovery focused swing weights resulted in more weight of support for alternatives involving translocations. The optimal alternative became the C*ombined strategy, with augmentations*, followed closely by the *Introduction strategy*, then the *Augmentation strategy* and *Combined strategy, without augmentations*. Compared to SMART analysis using the group mean swing weights, using the risk averse swing weights resulted in more weight of support for alternatives without translocations. The optimal alternative became the *Status quo strategy*, followed closely by the *Top-down mortality management strategy* then the *Habitat protection strategy*.

The weight of support for each alternative was also sensitive to lower values of the microbial mixing risk multiplier value (Figure 12). Incorporating the highest value of the microbial mixing risk multiplier elicited from the working group, 3, generated similar SMART analysis results as incorporating the group mean value of 1.6. However, incorporating the lowest value of the microbial mixing risk multiplier elicited from the working group, 0, resulted in identification of the *Augmentation strategy* as the optimal alternative, and the *Introduction strategy* and *Combined strategy, without augmentations* as the least optimal alternatives, in the SMART analysis.

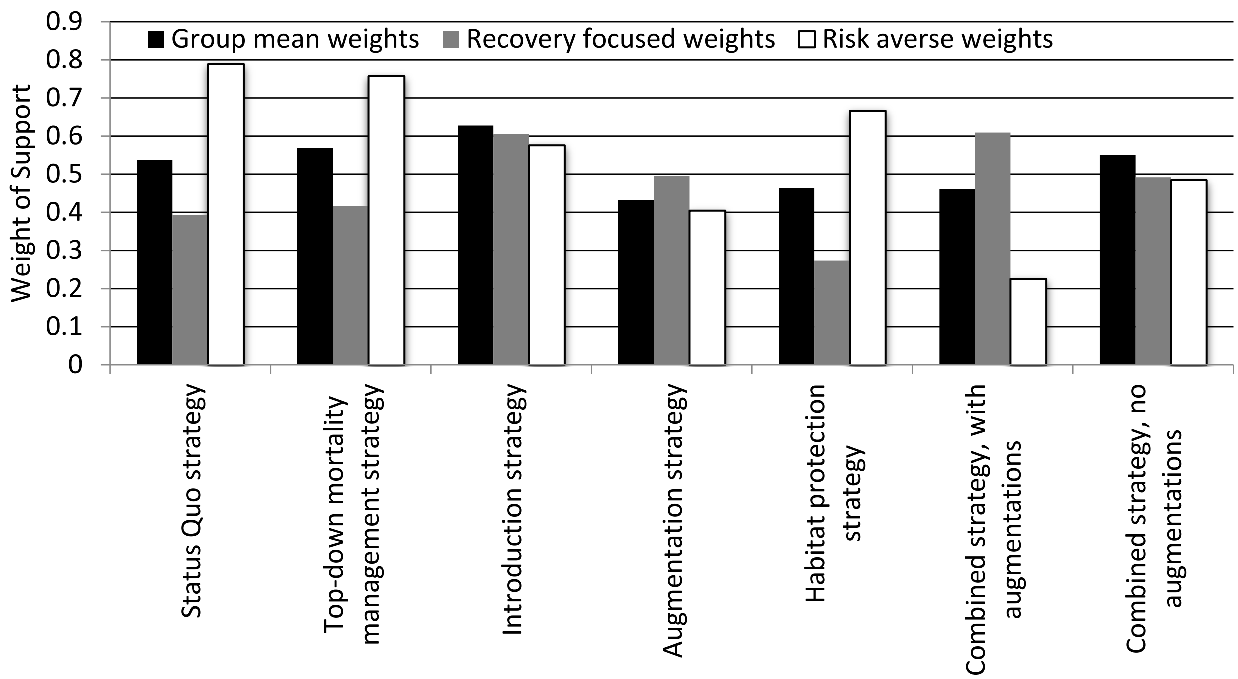

Figure 11. The effect of swing weighting scheme on the weight of support for each alternative. The weight of support for each alternative is the sum of normalized, weighted predictions for each alternative from the Simple, Multi-Attribute Rating Technique (SMART) analysis, using the mean microbial mixing risk multiplier value of 1.6.

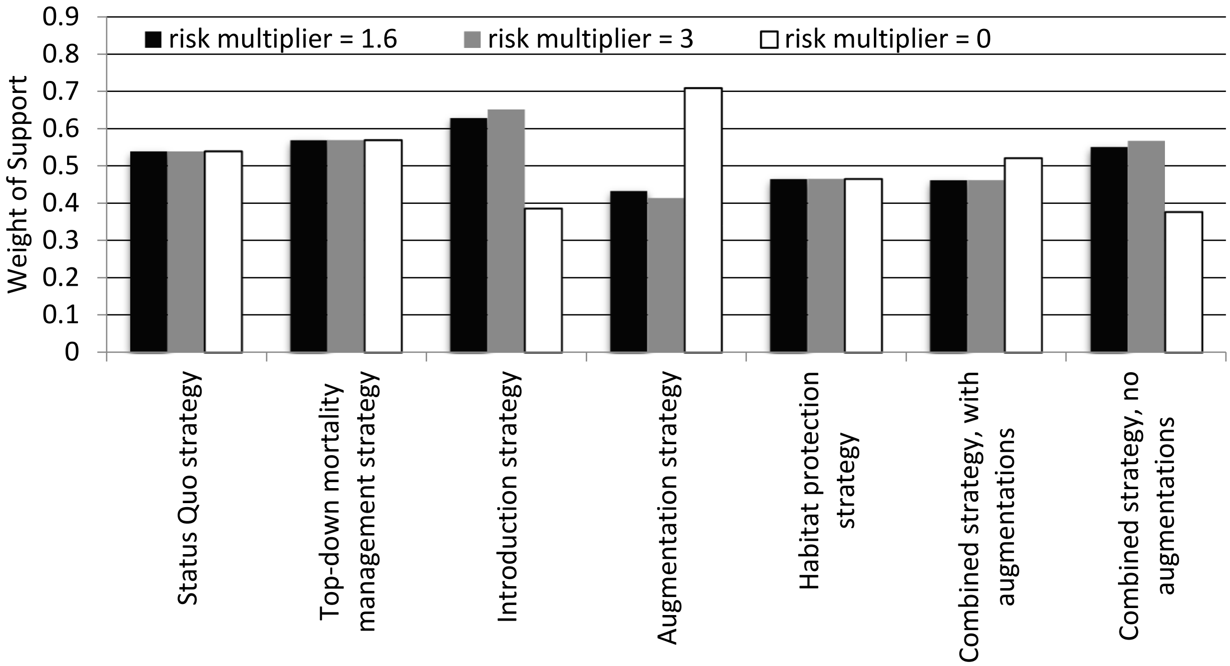

Figure 12. The effect of microbial mixing risk multiplier value on the weight of support for each alternative. The weight of support for each alternative is the sum of normalized, weighted predictions for each alternative from the Simple, Multi-Attribute Rating Technique (SMART) analysis, using the group mean swing weights. The group mean microbial risk multiplier value is 1.6, while 0 and 3 are the lowest and highest values elicited from the working group.

Conclusions, management strategy recommendations, and priority information needs

We used an SDM process to recommend management actions and priority information needs for mountain goats in Montana. The decision framework included overarching objectives, which the working group recommends pursuing to the extent possible, fundamental objectives with specific, quantitative measurable attributes, and management alternatives composed of actions designed to achieve fundamental objectives. The predicted consequences of each management alternative were made on the quantitative scale of each fundamental objective. Consequence predictions accounted for uncertainty in if and how climate change will affect mountain goat habitat, mountain goat demographics and population dynamics, and the risk of pneumonia epizootics in bighorn sheep and mountain goats. Based on these specific decision elements, we arrived at general conclusions to guide mountain goat management and research in Montana.

First, programs to implement the overarching objectives should be pursued for mountain goat management around the state. Efforts should be made to foster cooperative working relationships among jurisdictions managing mountain goats at the local, herd level and the administrative, agency level. In mountain goat herd units in which human development or recreation is sufficient to affect mountain goat distribution, efforts should be made to mitigate such impacts. When habituation occurs or is anticipated in mountain goat herds, management and education programs should be used to minimize or reverse it. Glacier National Park and other jurisdictions have developed some methods to reduce mountain goat habituation that may be applicable in herds under state of Montana jurisdiction. Other methods for more remote areas with lower staffing levels may need to be developed. When habitat is being lost to conifer encroachment within a herd range, and where logistically possible, forestry operations could be implemented to maintain mountain goat habitats where and if such efforts might help maintain or increase mountain goat populations. Every effort should be made to maximize the amount of public opportunity to hunt and view mountain goats, consistent with agency mandates to provide recreational opportunities. We note that harvest opportunity may need to be reduced in herds where harvest is known or thought to limit population growth, and FWP has found broad public support for such actions. Efforts to provide consumptive and non-consumptive opportunities related to mountain goats will help to build public support for mountain goat conservation and management, which should also be pursued with specific educational and information campaigns at local and larger levels.

Our decision analysis identified introductions to establish new mountain goat populations as a climate-change resilient strategy (Peterson et al. 2003) that should be pursued. We predict that new introductions will increase the area occupied by mountain goat populations, regardless of if or how climate change affects the mid-century distribution of mountain goat habitat. Management alternatives with new population introductions were consistently well-supported in our decision analyses. The weight of support for management alternatives with new population introductions was relatively insensitive to the variation in disease risk aversion we documented within our working group (Figure 11, Figure 12). New population introductions have been the rationale for most past translocations of mountain goats in Montana (Picton and Lonner 2008), and they have been successful in terms of increasing the area occupied and the total number of mountain goats in Montana (Smith and DeCesare 2017). The specific new population introductions in the management alternatives we considered included both reintroductions to native ranges where populations have been extirpated as well as introductions into previously unoccupied habitats (Tables 2, 4).

The amount of future gain in area occupied by mountain goat populations may be small, in part due to uncertainty in future climate conditions and their effects on mountain goat habitat, but positive gains in area occupied are predicted from alternatives with new population introductions under the full range of future climate scenarios we considered. New population introductions could be done in a strategic way that will help reduce uncertainty about their effects on the area occupied by mountain goats over the next 50 years. New population introductions could also be combined with other management actions that were well-supported in our decision analysis. For example, education and community involvement campaigns could be established to ensure local ownership and value for a newly-introduced population. New introductions could be paired with short-term efforts to reduce carnivore densities before and during the introduction to facilitate immediate population increase, which has improved the recovery and maintenance of other small populations of mountain ungulates (DeCesare et al. 2010, Hervieux et al. 2014).

New population introductions do have the potential to overlap the distribution of bighorn sheep herds, and therefore can pose a risk of pneumonia-associated pathogen transmission to bighorn sheep. We found a strong disease risk aversion effect, represented as risk averse swing weights on fundamental objectives and larger values of the microbial mixing risk multiplier, on the overall weight of support for any alternatives with mountain goat translocations, including new population introductions. We therefore recommend that any new population introductions overtly consider disease transmission risks, mitigate them where possible, and assure that affected stakeholders and agencies are willing to take the risks.

Reducing hunter harvest in small populations of mountain goats could have a large, positive effect on the number of populations meeting trend objectives. Harvest opportunity has already been substantially reduced in many areas (Smith and DeCesare 2017) and should be considered in other areas. Recent hunting regulation changes in Montana have also focused on reducing harvest of adult female mountain goats in some areas, and this should also be considered in other areas that are not meeting an increasing population trend objective. This recommendation is consistent with mountain goat management plans in neighboring jurisdictions that strictly limit and focus harvest on adult males (e.g., Alberta Sustainable Resource Development 2003, Idaho Department of Fish and Game 2019). Due to low inherent productivity, the substantial limiting effect of public harvest on small mountain goat populations is well-known (Hamel et al. 2006). However, we note that in introduced populations with high productivity, higher harvest rates may be useful for managing population sizes below carrying capacity to prevent forage over-utilization, population crashes, and population dynamics similar to those of small, struggling populations (Swenson 1985, Williams 1999).

Similarly, reducing predation from large carnivores by lowering their density through increased carnivore harvest is predicted to possibly have a large, positive effect on the number of mountain goat populations meeting increasing trend objectives. However, our predictive population model assumes this effect could be realized, without empirical evidence, and there is high uncertainty about the effect size due to the large uncertainty in mountain goat demography and population dynamics. This management action should therefore be considered in a research or learning context that will reduce our uncertainty about population dynamics and the effects of the action. An increased carnivore harvest strategy will also create conflict among the public, so if pursued it should be done in a manner that maximizes public support, where there is a likelihood of success, and with uncertainty in the outcome being transparently communicated.

Our predictions show that augmentations of herds not meeting population trend objectives might also have a large, positive effect on the number of mountain goat populations reaching trend objectives. Positive effects of augmentation on population dynamics of struggling herds has been the justification for some past translocations of mountain goats in Montana (Picton and Lonner 2008) and Idaho (Idaho Department of Fish and Game 2019) and is also the justification for the recent translocations of mountain goats from Olympic National Park to National Forests in the North Cascades (National Park Service 2018). However, augmentations also increase the number of herds exposed to pneumonia-associated pathogens and mix the associated microbial communities of the mountain goat and bighorn sheep herds being mixed. The strong disease risk aversion we documented among much of our working group had its largest effect on the overall weight of support for alternatives involving augmentations. Alternatives involving augmentations were among the most supported only when small values were used for the microbial mixing risk multiplier or the swing weights on fundamental objectives associated with disease risks. We therefore recommend that mountain goat herd augmentations only be considered in the context of increased disease risks, and associated aversion to disease risks, in a research or learning context. If pursued, augmentations should be conducted in a manner that facilitates reduction of uncertainties about their effects on mountain goat population dynamics. Augmentations should be pursued in areas where there is already an identified risk of extirpation in the recipient herd, such that tolerance for the additional disease risks is higher. Augmentations could also be paired with short-term efforts to reduce carnivore densities before and during the introduction to facilitate immediate population increase.

Area closures of important mountain goat habitats should only be considered in areas where impacts of human activities on mountain goat populations are relatively clear, because area closures are not predicted to have a substantial effect on the number of mountain goat populations meeting trend objectives. Our recommendation contrasts with management plans in some other jurisdictions (e.g., Alberta Sustainable Resource Development 2003), which rely heavily on area closures to protect mountain goat habitats. Montana has yet to see the level of human disturbance, and the associated impacts to mountain goat populations, that other states and provinces have, but we should be ready to pursue this action where it is needed. We predicted that area closures will increase social conflict more than any other action we evaluated. If pursued in Montana, area closures should be pursued in a publicly transparent way that clarifies the intention to protect struggling mountain goat herds for the public and decision makers to weigh against the human opportunities that would be lost. Further, the effects of area closures on mountain goat population trends that we did predict are based on our model structure and assumptions about the impacts of area closures on population dynamics, for which empirical data do not exist. These model assumptions should be evaluated with increased monitoring of mountain goat vital rates where area closures are undertaken, to help quantify the effects of these actions on mountain goat populations. Nevertheless, area closures could be important in specific mountain goat populations in Montana, to prevent loss of habitat function in struggling herds that become exposed to high levels of human disturbance.

In addition to the above management strategy recommendations, we identified two priority information needs for mountain goats in Montana, based on decision analysis results indicating a clear effect of these uncertainties on choice of management strategies. First is a need to decrease uncertainty about mountain goat population dynamics in Montana, which will affect our predictions and selection of optimal management strategies related to increasing the number of mountain goat herds meeting population trend objectives. Better population data on mountain goats has been an information need for over 5 decades in Montana (Mussehl and Howell 1971). Decreasing uncertainty about mountain goat demography and population dynamics is also a central part of mountain goat management plans in neighboring jurisdictions (Alberta Sustainable Resource Development 2003, Idaho Department of Fish and Game 2019).

This information need includes developing improved, Montana-specific estimates of mountain goat population sizes, vital rates, and age structures; and inferences regarding the effects of carnivore harvest, habitat protection, and translocations on mountain goat survival and fecundity. We estimated that EVPI>0 for information about mountain goat demography and population dynamics, despite the several, large sources of uncertainty we incorporated in our predictive population model. We also made several strong, simplifying assumptions in our predictive model, such as assuming a stable-age distribution from the Leslie matrix for very small populations, that mountain goat vital rates across Montana are the same as those recorded at one population in Alberta (Hamel et al. 2006, Côté and Hamel 2018), and that increasing carnivore harvest in mountain goat herd units, protecting their critical ranges from human use, and translocating mountain goats will increase the mean values and variance of survival and fecundity. These last assumptions lead to predictions of positive effects of taking these actions, yet no empirical mountain goat data exist to support these assumptions.

Relatedly, we need analyses to determine the viability of struggling mountain goat herds across western Montana, and whether some of these herds are at risk of extirpation. Our prediction time horizon for the number of mountain goat population units meeting trend objectives was 9 years, and we did not account for loss of occupied population units (area) that would result from extirpations of populations beyond that time frame. We therefore assume that small, struggling mountain goat herds will not become extirpated within our prediction time frame of 50 years for the area of occupied mountain goat habitat. This critical assumption likely results in positive bias in our predictions for alternatives that do not involve taking action to improve population trends in small, struggling herds. Further, we assumed that mountain goat populations were operating within 58 population units. Some of these units may actually consist of smaller, disconnected herds of mountain goats. If mountain goat populations are actually smaller than we assumed in our modeling exercises, extirpation probabilities would be even higher in those smaller herds. High probabilities of extirpation would likely affect the tolerance of decision makers for taking actions and risks, such as population augmentations, to forestall extirpation of smaller herds.

The second priority information need that we identified is related to pneumonia pathogens in mountain goats. This information need includes estimates of the pneumonia-associated pathogen communities in Montana mountain goat herds and quantification of the health and population effects of mixing pathogen communities when mountain goat and bighorn sheep herds are mixed during translocations. If mountain goat translocations are not going to be implemented, this information need is not critical because additional disease risks associated with translocations will not be incurred. If mountain goat translocations to establish new herds or to augment existing herds, or translocations of bighorn sheep into mountain goat herd units, will be implemented, our decision analysis results indicate that we can decrease the number of bighorn sheep and mountain goat herds at risk of pneumonia epizootics with more information about pneumonia pathogens. Disease risks can be reduced with more information about the pathogen communities of mountain goat and bighorn sheep herds with a focus on source and recipient areas first. This priority information need is very similar to that recently identified for mountain goats in Idaho (Idaho Department of Fish and Game 2019). Such sampling of pathogen communities in mountain goat and bighorn sheep herds will not always result in a clear decision regarding translocations because of limited sample sizes and incomplete knowledge about the etiology of pneumonia epizootics in these mountain ungulates (Cassirer et al. 2018). However, such sampling will permit informed decision-making regarding translocations and more accurate enumeration of risks.

The microbial mixing risk multiplier we used to represent risk tolerance for mixing pathogen communities of host mountain goat or bighorn sheep populations, while an accurate representation of real-world risk aversion among professional wildlife biologists and wildlife health staff, has a large effect on the predicted value of information about pneumonia pathogen communities and on the decision analysis overall. As the value of the microbial mixing risk multiplier is adjusted from 0-3 (the range elicited from the working group), management strategy alternatives involving mountain goat augmentations go from the most supported to the least supported in our decision analysis. More information on the biological effects of mixing microbial communities among mountain goat and bighorn sheep herds would be of great worth to informing mountain goat management going forward. Such information would help establish a biological rationale for the value used for the microbial mixing risk multiplier.

Related to biological information needs associated with pneumonia pathogens, we identified key social science needs. These include a better understanding of the risk tolerance among wildlife managers, decision makers, and the engaged public for pneumonia epizootics in bighorn sheep or mountain goat herds that arise from management actions. Risk attitudes are a function of personal values and vary among people (Keeney 1992). Information about the range of public tolerance for taking risks associated with translocations that result in mixing mountain goat and bighorn sheep herds would help inform actions chosen by decision makers, as would information about risk tolerances among non-governmental organizations that are vested specifically in mountain goat and bighorn sheep conservation. Risk tolerances of decision makers (elected and appointed officials) would also be informative for their decision making and for public transparency. Similarly, the relative weights placed on minimizing disease risks to bighorn sheep and mountain goats have a large effect on the optimal decision and whether augmentations should be undertaken or not. A better understanding of the relative importance among wildlife managers, decision makers, and the engaged public of achieving objectives related to minimizing disease risks versus other fundamental objectives is also a priority social science need. Importantly, risk tolerances should be quantified separately for management actions that could induce disease risks in struggling mountain goat herds that are facing extirpation, herds that are small and that we would like to increase, and related to the establishment of new herds.

Both biological information needs that we identified, related to uncertainties in population dynamics and disease risks in mountain goats, affect achievement of fundamental objectives and are affected by the management actions included in our alternatives. Because the management actions we included are likely to be repeated in time or across the state, these uncertainties could be reduced through development of an adaptive management program (Conroy and Peterson 2013). Focused research and monitoring programs could be implemented in concert with management actions in a way that decreases these uncertainties and improves the achievement of fundamental objectives in the future or in other areas. We also note that these information needs are closely related. For example, Montana-specific mountain goat population dynamics data will be key to understanding the effects of pneumonia pathogens (*sensu* Cassirer et al. 2013, Butler et al. 2018) and the effects of management actions such as translocations that create disease risks. These uncertainties might therefore be reduced in concert with one another in a carefully designed adaptive management program.

Alternatively, priority information needs could be addressed in succession, focusing on pneumonia pathogens in mountain goats first because of the larger effect of this information need on the overall decision. Addressing the information need related to mountain goat population dynamics should bolster our ability to increase the number of mountain goat herds meeting population trend objectives, but based on our decision framework and analysis, addressing this information need is unlikely to affect achievement of other fundamental objectives. Conversely, the biological and social information needs associated with pneumonia pathogens and disease risk tolerance would affect both the degree to which objectives related to minimizing disease risks to mountain goats and bighorn sheep can be achieved, as well as the overall optimal choice among management actions. Further, because of the strong effect of disease risk tolerance on the weight of support for management alternatives involving mountain goat translocations, and the potential for translocations to have large effects on the future area occupied by mountain goats populations and the number of mountain goat herds meeting population trend objectives, addressing the information need related to pneumonia pathogens in mountain goats will likely affect the achievement of multiple fundamental objectives.

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