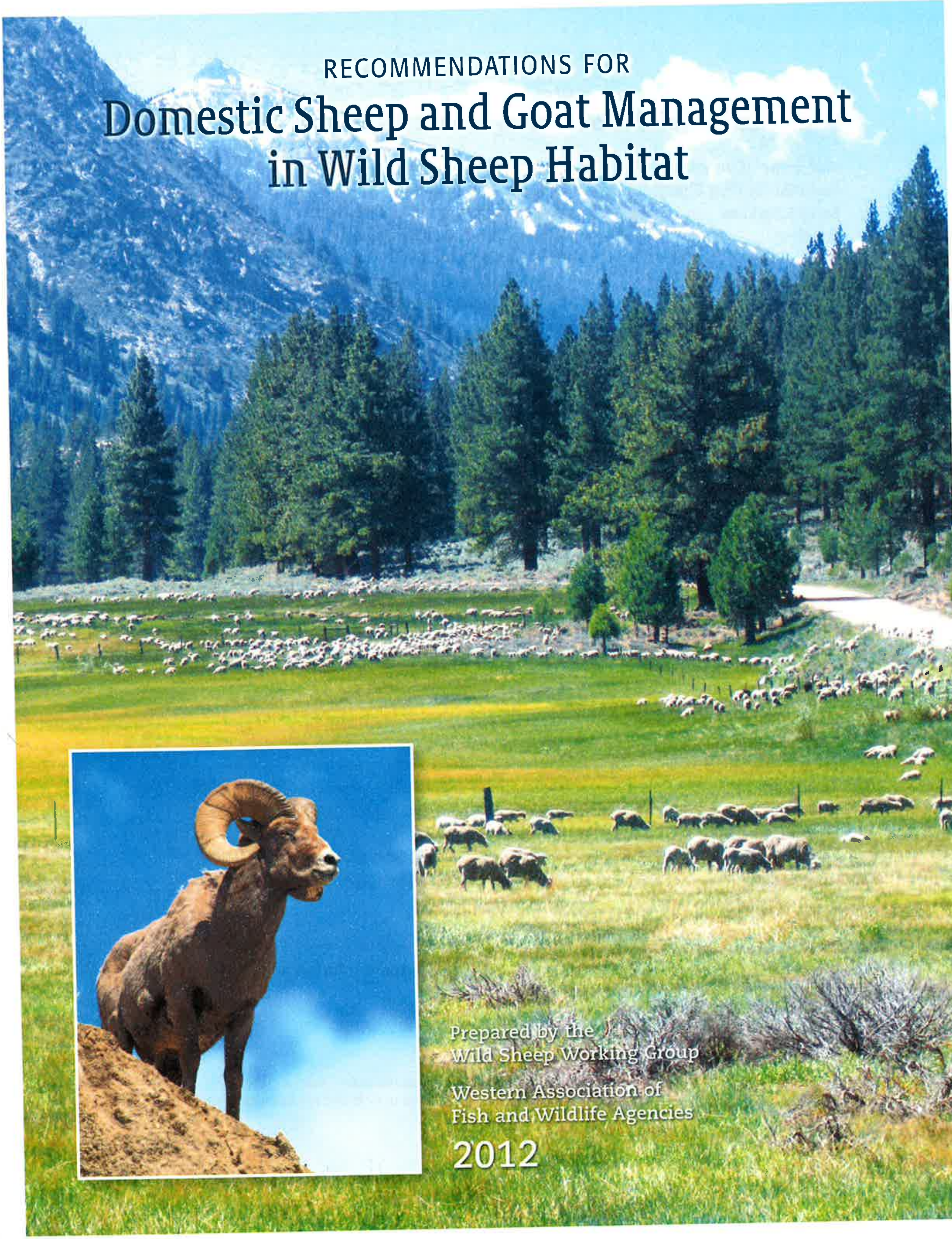
RECOMMENDATIONS FOR

Domestic Sheep and Goat Management in Wild Sheep Habitat



Prepared by the
Wild Sheep Working Group

Western Association of
Fish and Wildlife Agencies

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Executive Summary

Although the risk of disease transmission from domestic sheep or goats to wild sheep is widely recognized, a unified set of management recommendations for minimizing this risk has not been adopted by responsible agencies. These Western Association of Fish and Wildlife Agencies (WAFWA) recommendations were produced to help state, provincial, and territorial wild sheep managers, federal/crown land management agencies, private landowners and others take appropriate steps to eliminate range overlap, and thereby, reduce opportunities for transmission of pathogens to wild sheep.

Transmission of *Mannheimia haemolytica* from domestic sheep to bighorn sheep was irrefutably demonstrated by Lawrence et al. (2010) and provides justification sufficient for preventing range overlap and potential association of domestic sheep and goats with wild sheep. The higher the conservation value of a wild sheep population (e.g., federally or state listed, "sensitive species" status, native herds, transplant source stock, herds in areas with no history of domestic livestock presence), the more aggressive and comprehensive wild sheep and domestic sheep or goat separation management strategies should be.


Photo by: David Wetzel (Texas Bighorn Society)


Photo by: Tom Carlsen (MDEWP)

Practical solutions will be difficult, if not impossible to achieve until the risk of disease transmission from domestic sheep or goats to wild sheep is acknowledged by those responsible for wildlife and agricultural management. All parties benefit when risk is assessed and actively managed to minimize the potential for transmission of pathogens. The recommendations contained within this report are intended to help achieve that objective to benefit all sectors and are summarized as follows:

WAFWA agencies should:
(1) assess wild sheep conservation value/status and complete risk assessments of interspecies contact in a meta-population context; (2) remove wild sheep that have likely associated with domestic sheep or goats and develop a policy to promptly respond to wild sheep wandering from occupied wild sheep ranges; (3) thoroughly explore demographic consequences of translocations and conduct appropriate analyses of habitat suitability and risk of disease transfer prior to implementing any translocations; (4) coordinate with other agencies, land owners and stakeholders regarding management of domestic sheep or goats on or near ranges occupied by wild sheep; (5) fully consider the risk of disease transmission when issuing or commenting on permits/regulations associated with private lands used for domestic production; and (6) develop educational materials and outreach programs to interpret the risk of association between wild sheep and domestic sheep or goats.

Land management agencies should:
(1) reduce risk of association by eliminating overlap of domestic sheep or goat allotments or grazing permits/tenures within wild sheep habitat; (2) ensure that annual operating instructions or their equivalent include measures to minimize domestic association with wild sheep and confirm appropriate methods to remove stray domestic sheep or goats; and (3) manage wild sheep habitat to promote healthy populations in areas without domestic sheep or goats.

Wild sheep conservation organizations should:
(1) assist with educational/extension efforts to all parties; (2) negotiate alternatives and incentives for domestic sheep or goat grazers on public land to find alternatives to wild sheep habitat; and (3) advocate for and support research concerning disease and risk associated with domestic sheep and goats in proximity to wild sheep.

Domestic sheep and goat permittees/owners should:
(1) implement best management practices (BMPs) to prevent straying by domestic sheep or goats; and (2) establish protocols to respond to straying.

Private landowners should:
(1) educate themselves and work with wild sheep managers and advocates to support effective separation through a variety of site-specific mitigation measures; and (2) promptly report the potential or actual association between domestic sheep or goats and wild sheep.

Introduction

In January 2007, the Western Association of Fish and Wildlife Agencies (WAFWA), comprised of 23 state and provincial wildlife agencies from the western United States (U.S.) and western Canada, established a Wild Sheep Working Group (WSWG) to develop a report titled, "Recommendations for Domestic Sheep and Goat Management in Wild Sheep Habitat" (WAFWA 2007). Unanimously endorsed by WAFWA Directors in July 2007, that report provided recommendations to which state, provincial and federal agencies could tier their management actions. In August 2007, the report was forwarded to the heads of the U.S. Forest Service (USFS), Bureau of Land Management (BLM), National Park Service, U.S. Fish and Wildlife Service, Bureau of Reclamation, and Department of Defense. In July 2010, the report was revised (WAFWA 2010c) and has represented the official position of WAFWA on the management of domestic sheep and goats and wild sheep.

Scientific literature that has become available since July 2010 has been incorporated into this document to ensure that the recommendations contained herein remain current and robust, but the basic purpose, scope, and principles of the document remain unchanged. Additional editorial modifications are intended to improve the readability of the document. Information contained in this report is provided to assist BLM and USFS leadership with development of a unified policy addressing the grazing of domestic sheep or goats in wild sheep habitat on lands under the administration of those agencies. In addition, this document is intended to assist state, provincial, and territorial wild sheep managers, federal/crown land management agencies, private landowners and others take appropriate steps to eliminate range overlap, and thereby, reduce opportunities for transmission of pathogens to wild sheep. This revision was approved by the WAFWA Directors March 29, 2012, and supersedes all previous versions.


Photo by: Earl Nottingham (TPWD)


Photo by: Dr. Peri Wolff (NDOW)

In this paper we do not review and synthesize all available literature or evidence pertaining to the issue of disease transmission among bighorn sheep and domestic sheep and goats. We do, however, include relevant citations, results, literature, or analyses published since completion of our previous reports (WAFWA 2007, 2010c). We provide reasonable and logical recommendations based on the best available information to help achieve effective separation between wild sheep and domestic sheep or goats. We recognize it is impossible to achieve zero risk of contact or disease transmission; however, we also recognize there are many ways to reduce the probability of association between these species and, thereby, lower the overall risk of epizootics occurring in populations of wild sheep.


Photo by: David Wetzel (Texas Bighorn Society)


Photo by: Mike Pittman [illegible]

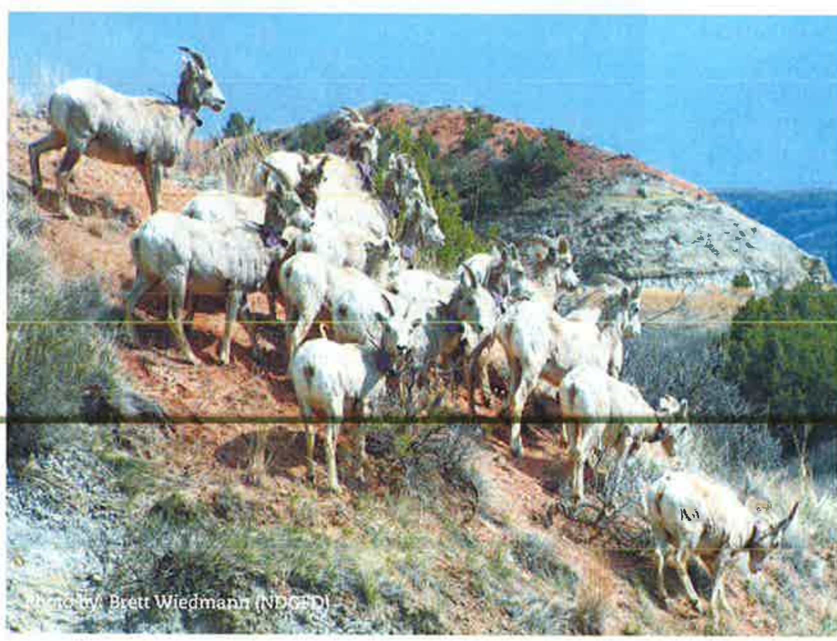


Photo by: Brett Wiedmann (NDGFD)

Background

Throughout substantial portions of their range, bighorn sheep (*Ovis canadensis*) experience periods when populations are depressed; those episodes generally are associated with epizootics of respiratory disease (Ryder et al.1994). Diseases have contributed to the decline of bighorn sheep populations in much of western North America (Beecham et al. 2007, CAST 2008) and many native herds declined to less than 10% of historical size. According to historical accounts, such declines coincided with the advent of domestic livestock grazing on ranges occupied by bighorn sheep (Warren 1910, Grinnell 1928, Schillinger 1937, Honess and Frost 1942, CAST 2008). Epizootics among native bighorn herds were reported in various locations following European settlement and establishment of domestic livestock grazing throughout the central and southern Rocky Mountains. These observations may reflect the introduction of novel bacterial pathogens (including some strains of *Pasteurella [Mannheimia]* spp.) to naïve bighorn populations beginning in the late 1800s (Grinnell 1928, Skinner 1928, Marsh 1938, Honess and Frost 1942, Miller 2001).

Over the past 30 years, increasing evidence has underscored the potential risk of disease transmission from domestic sheep or goats to wild sheep (McQuivey 1978, Hunt 1980, Jessup 1982, Foreyt and Jessup 1982, Goodson 1982, Onderka and Wishart 1984, Jessup 1985, Black et al.1988, Coggins 1988, Festa-Bianchet 1988, Onderka and Wishart 1988, Onderka et al.1988, Schwantje 1988, Callan et al.1991, Coggins and Matthews 1992, Foreyt 1994, Foreyt et al. 1994, Cassirer et al.1996, Foreyt and Lagerquist 1996, Martin et al. 1996, Coggins 2002, Rudolph et al. 2003, Jenkins et al. 2007, Rudolph et al. 2007, George et al. 2008, Jeffress 2008, Lawrence et al. 2010). Moreover, a number of recent risk assessments and reviews (Beecham et al. 2007, CAST 2008, Baumer et al. 2009, USAHA 2009, WAFWA 2009, Croft et al. 2010, USDA Forest Service 2010a, b; Wehausen et al. 2011), conservation management strategies or plans (Colorado Division of Wildlife 2009, Montana Department of Fish, Wildlife, and Parks 2009), modeling exercises (Clifford et al. 2009, Cahn et al. 2011), and many wildlife biologists and wildlife veterinarians (Gross et al. 2000, Singer et al. 2000, Dubay et al. 2002, Epps et al. 2004, Garde et al. 2005, Jansen et al. 2006, Foreyt et al. 2009) have focused on risks associated with contact between wild sheep and domestic sheep or goats. Many of the aforementioned investigators and participants in workshops conducted throughout the western US (California, Arizona, Utah, and Idaho),

have recommended temporal or spatial separation of domestic sheep or goats from wild sheep to reduce the potential for disease in the latter.

Disease Transmission

Although domestic animals have been selected for their ability to live at high densities and for their resilience to infectious diseases (Diamond 1997), two-way transmission of certain diseases (e.g., paratuberculosis, some enteric pathogens and parasites) between wild sheep and domestic sheep or goats in shared habitats can occur (Garde et al. 2005). However, the most important and ecologically significant transmission in this context is from domestic sheep or goats to wild sheep.

Winter 2009-2010 bighorn sheep pneumonia die-offs (totaling an estimated 880 bighorns) in Montana, Nevada, Washington, Utah, and Wyoming have reduced bighorn numbers in at least 9 herds, either through direct mortality or agency removal (i.e., "culling") of bighorn sheep exhibiting symptoms of respiratory infections (Edwards et al. 2010, WAFWA 2010b). Domestic sheep and goats were known to occur within or near occupied bighorn sheep ranges and within normal bighorn movement zones, and association between wild sheep and domestic sheep or goats is known to have preceded at least one of these die-offs, was likely in 2 others, and was possible in 4 more (WAFWA 2010b).


Photo by: Donny Martorello (WDFW)

Die-offs of wild sheep populations and individual animals have occurred in the absence of reported association with domestic sheep or goats (Aune et al. 1998, UC-Davis 2007). However, when contact between wild sheep and domestic sheep or goats has been documented, the pattern and severity of die-off is typically greater than when otherwise is the case (Onderka and Wishart 1984, Martin et al. 1996, Aune et al. 1998, George et al. 2008).

It is generally acknowledged (Garde et al. 2005, CAST 2008) that thinhorn sheep (*Ovis dalli* spp.) in Alaska and northwestern Canada are likely naïve to exposure to many organisms commonly carried by domestic species, compared to wild sheep occurring in southern Canada and the continental U.S. Until this is confirmed and the effects of exposure to infectious organisms are clearly understood, it is essential that no association occurs between thinhorn sheep and domestic sheep or goats.


Photo by: Ernie Finch


Photo by: John Kanta (SDGFP)


Photo by: Ted Borda (Borda Land & Sheep Company)


Photo by: Ted Borda (Borda Land & Sheep Company)

Effective Separation

WAFWA defines "Effective Separation" as spatial or temporal separation between wild sheep and domestic sheep or goats to minimize the potential for association and the probability of transmission of diseases between species. WAFWA advocates that effective separation should be a primary management goal of state, provincial, territorial and federal agencies responsible for the conservation of wild sheep, based on evidence that domestic sheep or goats can transfer pathogens to wild sheep. Literature (reviewed by Wehausen et al. 2011) and experimental evidence (Lawrence et al. 2010) support the goal that domestic sheep or goats should not concurrently occupy areas where conservation of wild sheep is a clearly stated management goal.

Effective separation does not necessarily require removal of domestic sheep or goats in all situations. However, the option of removing domestic sheep or goats should be included in an array of alternatives available to address this issue. In fact, some collaborative working groups (USAHA 2009) have recommended domestic goats not be allowed to graze in occupied bighorn sheep habitat because of their gregarious nature and tendency to wander. We are aware of the continuing debate and discussion (CAST 2008, USAHA 2009) between wildlife advocates and some domestic sheep or goat industry proponents and resource managers regarding the credibility or scientific merit of past findings; that debate is founded largely on criticisms of experimental design or rigor, and limitations of drawing inferences about natural disease events when compared to controlled experiments in confined settings. However, it is WAFWA's collective opinion that enough is known about potential pathogen transmission from domestic sheep or goats to wild sheep that efforts toward achieving effective separation are necessary and warranted.

Reducing risk of disease transmission on the landscape by minimizing or preventing association between wild and domestic sheep or goats is a key management strategy for WAFWA agencies (e.g., Colorado Division of Wildlife 2009, Montana Department of Fish, Wildlife and Parks 2009). Legislation in Utah (House Bill 240 Supplement, 2009), Wyoming (Senate Enrolled Act No. 30, 2009) and Idaho (Senate Bill 1232 amended, 2009) provides direction, authority and responsibilities for addressing feral or stray livestock that pose a disease transmission risk. Further, recent court rulings (e.g., U.S. District Court, Idaho Case 09-0507-BLW) have mandated separation between domestic sheep or goats and bighorn sheep, including mandatory non-use of grazing allotments where effective separation could not be assured.

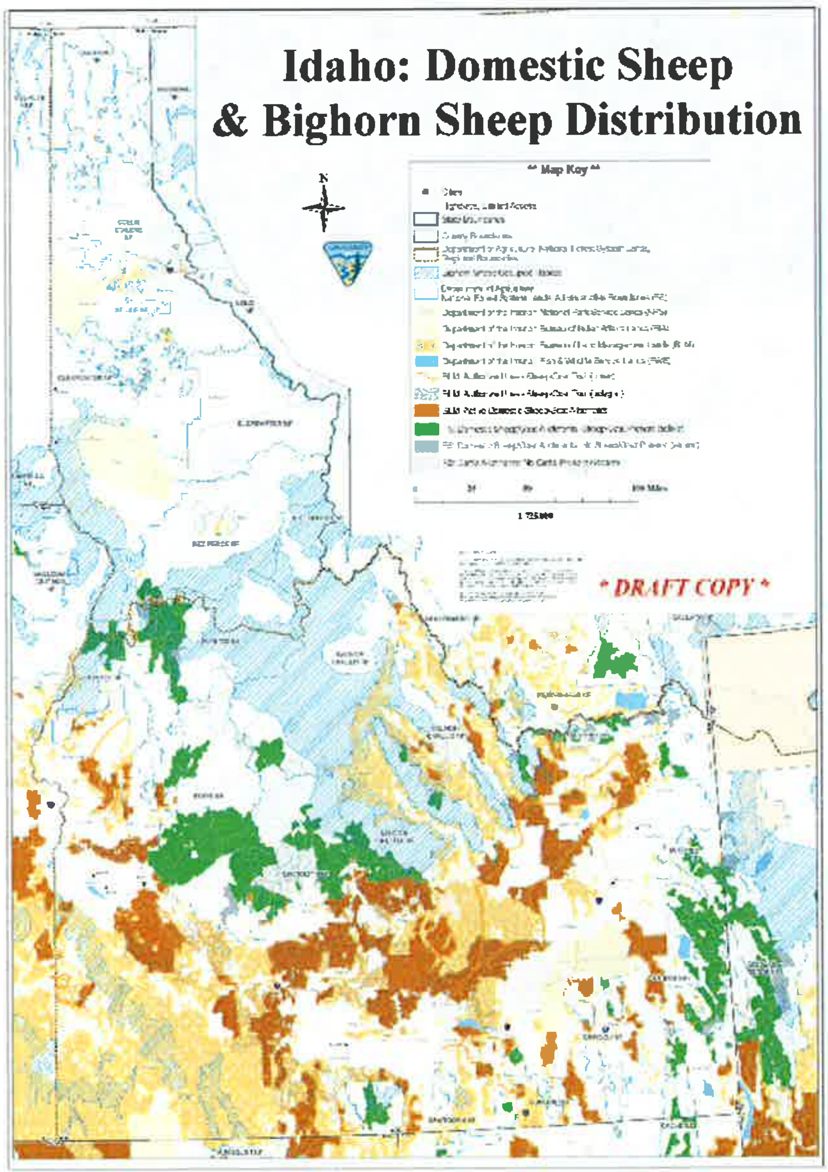
Principal federal land management agencies in the western U.S., BLM and USFS, continue to review, revise, and update policies on the management of domestic sheep or goats in wild sheep habitat (USDI BLM 1992, 1998, 2010; USDA Forest Service 2009). Additionally, several administrative units of the USFS (Northern Region, Rocky Mountain Region, Southwest Region, Intermountain Region, and the Pacific Southwest Region) have designated bighorn sheep as a "Sensitive Species," thereby mandating special management emphasis. This includes: thorough reviews and analyses of management actions that could affect populations of bighorn sheep or their habitat to ensure their viability and to preclude demographic trends that would result in the need for Federal listing.

An interagency GIS-based decision-support tool and GIS coverage maps that overlay current bighorn sheep distribution with vacant and active domestic sheep or goat grazing allotments and trailing routes were finalized for 14 western states (WAFWA 2010a). These maps identify areas where association between domestic sheep or goats and bighorn sheep could occur on, or adjacent to, lands managed by BLM or USFS, and also identify areas that could provide spatial separation. The maps further provide a context for national policy development, and help identify situations where proactive management is necessary to minimize risk of association. Although risk of disease transmission from domestic sheep or goats to wild sheep is widely acknowledged by wildlife and land management agencies, a unified set of management guidelines for minimizing this risk has not yet been adopted.

In some cases, results of contact between domestic sheep or goats and wild sheep have been severe enough to endanger entire populations of the latter. In Idaho, legislation (Senate Bill 1232 amended, May 2009) mandated collaboration between the Idaho Department of Fish and Game and domestic sheep grazing permittees that identified BMPs to achieve effective separation between domestic sheep and wild sheep on both public and private lands. In specific situations, implementation of BMPs could lead to a reduced risk of association. In particular, BMPs implemented in open, gentle terrain where domestic sheep or goats can be easily controlled and monitored can reduce risk of association (Schommer 2009). Nevertheless, BMPs that work in one situation may not work in other situations (Schommer 2009).

Consequently, we recommend that managers take appropriate steps to minimize opportunities for association and, thereby, the potential for disease transmission in all situations.

Photo by: Bighorn Institute



Provided by: Chans O'Brien (USFS)

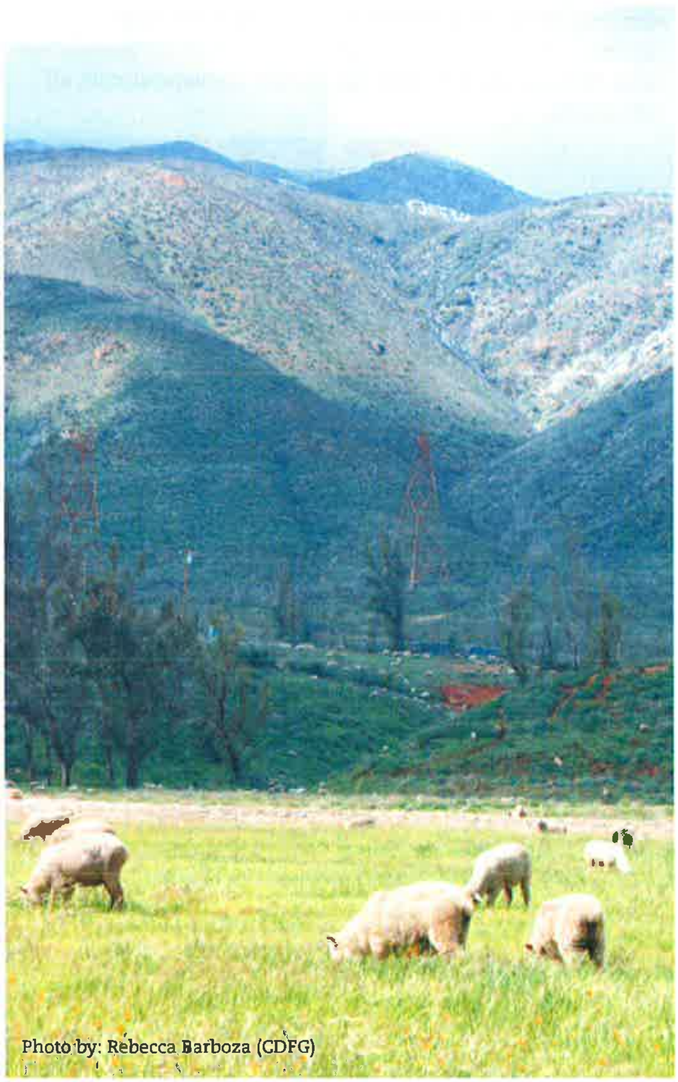

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Photo by: Larry Kruckenberg

Management Recommendations

The recommendations that follow can be applied to state, provincial, and territorial wildlife agencies, federal/crown land management agencies, wild sheep conservation organizations, domestic sheep or goat producers or permittees, and private landowners, and have been strategically assigned to logical categories. It is imperative, however, that readers recognize these recommendations typically apply to multiple parties, and that they further recognize that a multi-disciplinary and collaborative approach will produce the best outcomes, both for wild sheep and for producers or permittees. Definitions of various terms used throughout this document are provided in Appendix A.

Although these recommendations have been developed by a working group largely comprised of wildlife agency personnel, cooperation between numerous concerned parties is critically important to deriving on-the-ground solutions (USAHA 2009, Wild Sheep Foundation 2011). Among these are state, provincial, and territorial wildlife agencies; federal/crown land management agencies; First Nation or tribal representatives; domestic sheep or goat producers or grazing permittees; agricultural industry representatives; wild sheep conservation organizations; environmental groups; academic institutions; and interested individuals. As a result of information contained herein, it is our hope that collaborative discussions will occur and that those discussions yield results in the form of innovative and collaborative site-specific delivery of programs such as the British Columbia Wild/Domestic Sheep Separation Program and the Wyoming Statewide Domestic Sheep/Bighorn Sheep Interaction Working Group.

Many anthropogenic and environmental factors (CAST 2008) influence the demographics and viability of wild sheep populations. Some factors affecting wild sheep population performance can be managed while others cannot. Nevertheless, the guiding principle of our effort has been "to seek effective separation" between wild sheep and domestic sheep or goats. There is no "one size fits all" risk assessment of respiratory disease transmission between wild sheep and domestic sheep or goats. However, a comprehensive risk assessment (qualitative and quantitative) is a critically important component for managing the potential for disease transmission.

We recommend that wild sheep managers design and implement management strategies by taking the first step of assessing and prioritizing conservation value and relative importance of wild sheep populations. The greater the conservation value and the greater the risk of association with domestic sheep or goats, the more aggressive and comprehensive a strategy to ensure effective separation should be. To ensure that is the case, we offer the following:

RECOMMENDATIONS TO WAFWA AGENCIES

■ Historic and suitable but currently unoccupied wild sheep range should be identified, evaluated, and compared against currently-occupied wild sheep distribution and existing or potential areas where domestic sheep or goats may occur.

■ Risk assessments should be completed at least once per decade (more often if warranted) for existing and potential wild sheep habitat. These assessments should specifically identify where and to what extent wild sheep could interface with domestic sheep or goats, and the level of risk within those areas.

■ Following completion of site or herd-specific risk assessments, any translocations, population augmentations, or other restoration and management strategies for wild sheep should minimize the likelihood of association between wild sheep and domestic sheep or goats. Agencies should:

- Avoid translocations of wild sheep into areas with no reasonable likelihood of effective separation from domestic sheep or goats.
- Re-evaluate planned translocations of wild sheep to historical ranges as potential conflicts, landscape conditions, and habitat suitability change.
- Recognize that augmentation of a wild sheep herd from discrete source populations poses a risk of pathogen transfer (CAST 2008) and thus, only use source stock verified as healthy through a proper health assessment (WAFWA 2009) for translocations. Source herds should have extensive health histories and be regularly monitored to evaluate herd health. Wild sheep managers should evaluate tradeoffs between anticipated benefits such as demographic, behavioral and genetic interchange, and the potential consequences of mixing wild sheep from various source herds.
- Develop and employ mapping or modeling technology as well as ground based land use reviews prior to translocations to compare wild sheep distribution and movements with distribution of domestic sheep or goats. If a translocation is implemented and association with domestic sheep or goats occurs, or is likely to occur beyond an identified timeframe or pre-determined geographic area, domestic sheep or goat producers should be held harmless.

■ The higher the risk of association between wild sheep and domestic sheep or goats, the more intensively wild sheep herds should be monitored and managed. This is particularly important when considering "new" vs. "augmented" wild sheep populations.

- Site-specific protocols should be developed when association with domestic sheep or goats is probable. For example, decisions concerning percentage of translocated wild sheep that must be radio-collared


Photo by: Mike Cox (NDOW)

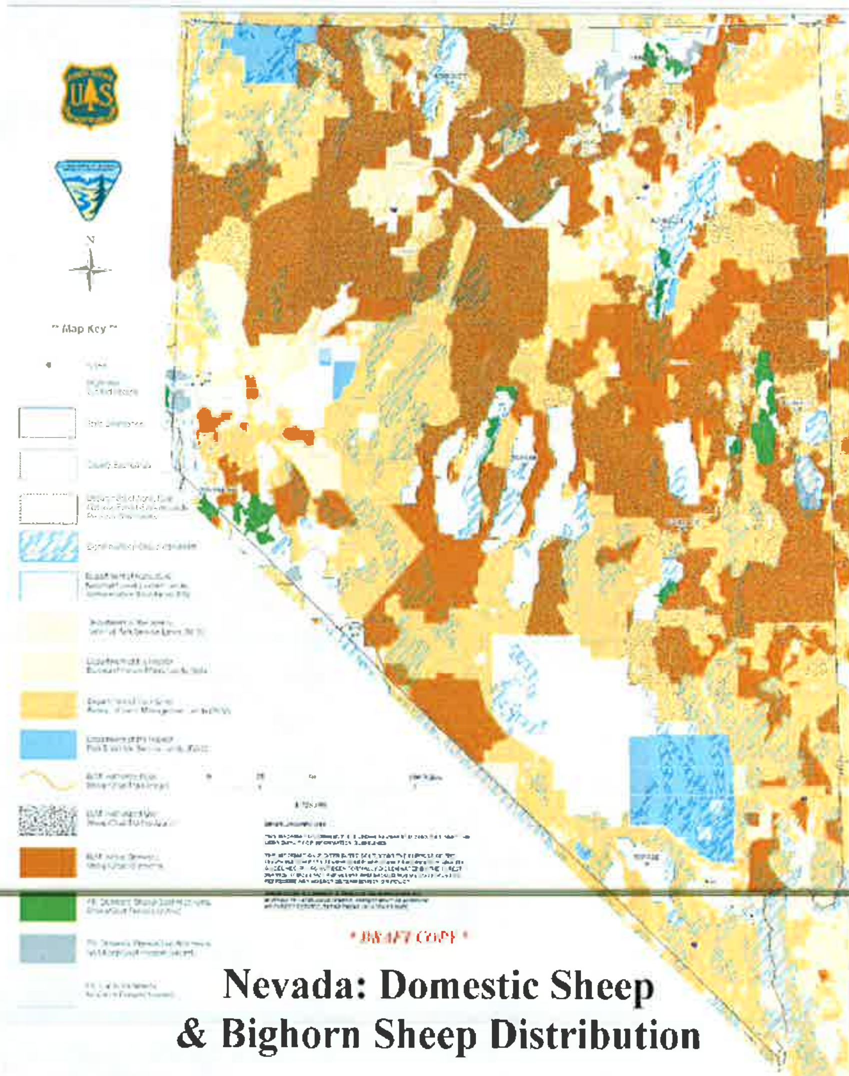
Photo by: Chase Fountain (TPWD)

for achieving desired monitoring intensities should in part, be based upon the subsequent level of risk of association with domestic sheep or goats.

- Intensive monitoring provides a mechanism for determining proximity of wild sheep to domestic sheep or goats and for evaluating post-release habitat use and movements.
- Budgets for wild sheep translocation projects should include adequate funding for long-term monitoring.

■ Wild sheep managers should identify, analyze, and evaluate the implications of connectivity and movement corridors between largely insular herds comprising a meta-population against opportunities for increased association with domestic sheep or goats. Analyses should include distribution and continuity (Mack 2008) among populations of wild sheep and the anticipated frequency of movement among or within wild sheep range. In doing so, the benefits of genetic interchange and its resultant implications for population viability, must be weighed against the risks of disease transmission (Bleich et al. 1990), especially if dispersing or wandering wild sheep could travel across domestic sheep or goat grazing allotments or trailing routes, private land holdings or other areas where the potential transfer of endemic pathogens from an infected wild herd to a naïve herd could occur.

■ Removal of wild sheep known, or suspected to have closely associated with domestic sheep or goats is considered to be an effective management tool. Atypical movements by wild sheep can heighten risk of association with domestic sheep or goats. Additional measures to achieve effective separation should be implemented if such association occurs. However, removal of wild sheep from occupied, normally-anticipated wild sheep range is not always the best management option. Continuous risk of association exists during active grazing seasons when domestic sheep or goats are grazed within normally-anticipated wild sheep range. Thus, removal of individual wild sheep is an ineffective method for maintaining separation, and has potentially negative consequences for population viability. Removal of wild sheep should occur only after critical evaluation and further implementation of measures designed to minimize association and enhance effective separation.



Provided by: Chans O'Brien (USFS)

■ Wild sheep populations should have pre-determined population objectives, and should be managed at agreed-upon densities to minimize the potential for dispersal. Because some dispersal occurs regardless of population density, some risk of association is always present if domestic sheep or goats are within range of dispersing wild sheep.

■ Agencies should develop a written protocol to be implemented when association between wild sheep and domestic sheep or goats is confirmed. Notification requirements, appropriate response and post-contact monitoring options for both domestic sheep and goats and dispersing or wandering wild sheep should be included. Moreover, wildlife agencies should collaborate with agricultural agencies, land management agencies, producers and permittees, grazing industry representatives,

and wild sheep advocates to develop an effective, efficient, and legal protocol to be implemented when feral or abandoned domestic sheep or goats threaten to associate with wild sheep but for which no owner can be identified. Written protocol examples are provided in Appendix B (British Columbia Fish, Wildlife and Habitat Management Branch) and Appendix C (Wyoming Game and Fish Department).

- Wildlife agencies should develop databases as a system to report, record, and summarize association between wild sheep and domestic sheep or goats and its outcome; the WAFWA WSWG website (http://www.wafwa.org/html/wswg.shtml) would be a logical host. Further, wildlife managers and federal/crown land managers should encourage prompt reporting by the public of observed proximity between wild sheep and domestic sheep or goats.

- Wild sheep managers should coordinate with local weed or pest management districts, or other applicable agencies or organizations involved with weed or vegetation management, to preclude the use of domestic sheep or goats for noxious weed or vegetation control in areas where association with wild sheep is likely to occur. Agencies should provide educational information and offer assistance to such districts regarding disease risks associated with domestic sheep or goats. Specific guidelines (Pybus et al. 1994) have already been developed and implemented in British Columbia, and are available at: http://www.for.gov.bc.ca/hfp/publications/00006/.

- Specific protocols for sampling, testing prior to translocation, and responding to disease outbreaks should be developed and standardized to the extent practical across state and federal jurisdictions. Several capture and disease-testing protocols have been developed and are available to wild sheep managers (Foster 2004, UC-Davis 2007, WAFWA 2009). Protocols should be reviewed and updated as necessary by the WAFWA Wildlife Health Committee (WHC) and presented to WAFWA Directors for endorsement. Once endorsed, agencies should implement the protocols, and the WHC should lead an effort to further refine and ensure implementation of said protocols.

- Agencies should coordinate and pool resources to support the ongoing laboratory detection and interpretation of important diseases of wild sheep. Furthermore, wild sheep managers should support data sharing and development and use of standardized protocols (WAFWA 2009). Interagency communication between wildlife disease experts such as the WAFWA Wildlife Health Committee (WHC) should be encouraged to enhance strategies for monitoring, managing and improving health of wild sheep populations through cooperative efforts.

- Wild sheep management agencies should develop educational materials and outreach programs to identify and interpret the risk of association between wild sheep and domestic sheep or goats for producer groups, owners of small and large farm flocks, animals used for packing and 4-H animals. In some cases, regulation may be necessary to maintain separation.

RECOMMENDATIONS TO BLM, USFS, PARKS, PROTECTED AREAS AND OTHER APPLICABLE LAND MANAGEMENT AGENCIES

- Joint federal land management agency guidelines on management of domestic sheep or goats in wild sheep habitat should be developed and included in broad agency policy documents. Guidelines should be based on the need to minimize risk of association and provide effective separation between domestic sheep or goats and wild sheep.


Photo by: Todd Nordeen (NGPC)

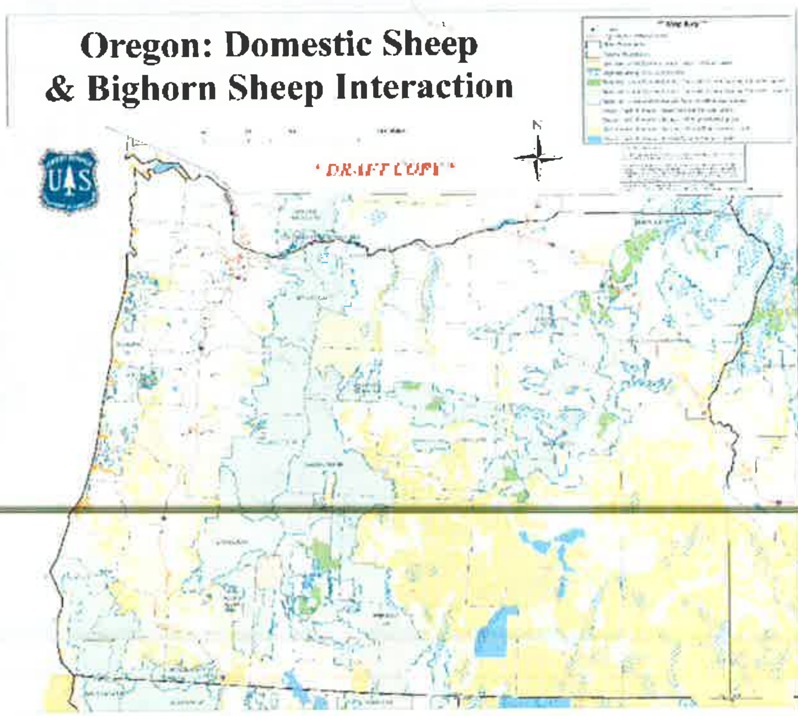

Photo by: Debra Hamilton (CDFG)

Management Recommendations

Approved guidelines should not include an automatic "sunset" provision or expiration date but, if there is a maximum longevity (i.e., a "sunset clause") specified by federal policy and if appropriate and timely review cannot be completed, guidelines should remain in effect, rather than becoming obsolete, until any mandated review can be completed.

- The use of domestic sheep or goats as pack animals by persons that travel in identified wild sheep habitat should be prohibited by the appropriate management agency (e.g., USDA Forest Service 2011). Where legislation or regulations are not already in place, an outreach program to inform potential users of the risks associated with that activity should be implemented to discourage use of domestic sheep or goats as pack animals.

Photo by: Ted Borda (Borda Land & Sheep Company)



Provided by: Chans O'Brien (USFS)

- Land management agencies that regulate or are responsible for domestic sheep or goat grazing allotments, trailing routes, vegetation management, use as pack stock, or any other uses involving domestic sheep or goats should only authorize such use(s) outside of occupied wild sheep range.

- Land management agencies should require immediate notification by permittees and their herders of association between wild sheep and domestic sheep or goats and in no case should it be more than within 24 hours of any such event. Notification procedures, including phone numbers and contact information for permittees and use of satellite phones in backcountry settings, should be outlined in Annual Operating Instructions for grazing allotments and trailing permits, and should include consequences for failure to report.

- Land management agencies should map active and inactive domestic sheep or goat grazing allotments and trailing routes, including information on dates of use and contact information for responsible grazing or trailing permittees.

- Land management agencies must ensure that advance written instructions (such as USFS Annual Operating Instructions) exist, and that they address management, retrieval, and disposition of domestic sheep or goats present on public lands prior to or after permitted grazing or trailing dates.

- Land management agencies should work collaboratively with state, provincial, and territorial wildlife and agricultural interests to develop written agreements that address management, retrieval, and disposition of domestic sheep or goats occupying public lands where there is no permitted use. Such agreements should also address the presence of feral sheep or goats and other exotic ungulates, especially ovines such as aoudad, red sheep, urial, or argali that are detected on public lands.

- Land management agencies should review domestic sheep allotment boundaries or other use areas, such as trailing routes, and reconfigure boundaries or routes to avoid or minimize overlap with occupied wild sheep habitat. Techniques available to accomplish this include the use of geographic or topographic

barriers that enhance species separation, and temporal or spatial separation resulting from implementation of novel domestic sheep or goat grazing management strategies.

■ Land management agencies should undertake habitat enhancements that improve wild sheep habitat outside allotment boundaries in an effort to attract wild sheep away from domestic sheep allotments.

■ Land management agencies should undertake water developments to divert wild sheep away from domestic sheep allotments or domestic sheep or goats away from areas used by wild sheep.

■ Land management agencies should ensure that Annual Operating Instructions require careful management and vigilant herding to minimize potential association between wild sheep and stray domestic sheep or goats. A count-on, count-off inventory of domestic sheep or goats must be required as a condition of operation with follow-up provisions to account for missing livestock.

■ In areas of high risk of association, trucking should be required to minimize risks associated with trailing. Trucking of domestic sheep or goats is preferred to trailing because there is less chance of straying and, thereby, less likelihood of association with wild sheep, particularly when domestic sheep are in estrus.

■ Land management agencies should require marking of all permitted domestic sheep and goats to provide for rapid ownership identification of stray animals.

■ In the event of trailing, on-site compliance monitoring to minimize strays must be conducted by the permittee or the land management agency.

■ Land use or resource management plans should explicitly address the potential for domestic sheep or goats to associate with wild sheep. Land use plans should evaluate the suitability of permitting activities involving domestic sheep or goats, and determine the best course of action with respect to wild sheep conservation. Plans should also identify general areas of public land where domestic sheep or goats cannot be permitted for weed control, commercial grazing, recreational packing, vegetation management, or other uses.

■ Land management agencies should coordinate with appropriate entities involved in weed control programs that use domestic sheep or goats on public or Crown lands (Pybus et al. 1994), adjoining private lands, or state, provincial, and territorial wildlife habitat management areas to minimize risk of association between domestic sheep or goats and wild sheep.

■ Within occupied or suitable wild sheep habitat, where topography, vegetation, and other parameters allow, conversions of allotments from domestic sheep or goats to types of domestic livestock that pose a lower risk of disease transmission to wild sheep should be implemented.

■ Within suitable, historic wild sheep habitat not currently occupied by wild sheep, agencies should not convert cattle grazing allotments to domestic sheep or goat grazing, or allow trailing if restoration of wild sheep populations is an agency goal.


Photo by: AZGFD


Photo by: Justin Binfet (WGFD)

Management Recommendations

■ Under emergency conditions, stocking of allotments not currently under permit to domestic sheep or goats should be permitted only after an adequate risk assessment has been completed. Any such assessment must include appropriate documentation and the conclusion that effective separation can be assured, and can be accomplished via project-level NEPA analysis.

■ Land management agencies should incorporate state, provincial, or territorial wild sheep management plans either in, or as supplements to, federal resource or land use management plans, and collaborate with wildlife agencies to ensure comprehensive risk assessments (Clifford et al. 2009, USDA Forest Service 2010a, b) of domestic sheep or goat grazing allotments or trailing routes in wild sheep habitat are thorough and complete. To accomplish this objective, training adequate to allow the preparation of such assessments must be provided.

Photo by: Mike Cox (NDOW)

■ Where mandatory buffer zones (frequently cited as a minimum of 9 airline miles [14.5 km]) between domestic sheep or goats and wild sheep have been used to minimize association, it should be recognized that buffer zones apply to herds or populations of wild sheep, rather than individual wandering wild sheep. In some cases, buffer zones have been effective in reducing association between wild sheep and domestic sheep or goats. However, in contiguous wild sheep habitat where movements by wild sheep have the potential to exceed *a priori* expectations, buffer zones may not be effective or practical (Schommer and Woolever 2001).

■ Topographic features or other natural or man-made barriers (e.g., fenced, interstate highways) can be effective in minimizing association between wild sheep and domestic sheep or goats. Site-specific risk assessments should be completed to evaluate the efficacy of using natural barriers, defined buffer zones, or other actions to minimize risk of contact. Given the wide range of circumstances that exists across jurisdictions, buffer zones may not be needed in all situations. Conversely, buffer zones should not be precluded as an effective method to address potential association between wild sheep and domestic sheep or goats.

■ Land management agencies, in collaboration with jurisdictional domestic sheep or goat health agencies, should work with producers and permittees to prevent turnout or use of sick or diseased domestic sheep or goats on grazing allotments and trailing routes. Sick or diseased domestic sheep or goats can increase risk of association with wild sheep because they likely are less able to keep up with their bands and are more prone to straying. Sick or diseased animals observed on the range should be reported to land management agency personnel immediately, and inter-agency coordination to address the situation should promptly occur. Further, responsible agencies must require that domestic sheep or goats are in good health before being turned out. For example, Alberta and British Columbia have developed health certification protocols (Pybus et al. 1994) that must be complied with before domestic sheep are turned out for vegetation management in conifer regeneration efforts (available at: http://www.for.gov.bc.ca/hfp/publications/00006/). We emphasize that the higher the risk of association between domestic sheep or goats with wild sheep, the higher the certainty of domestic animal health should be. Further, it must be recognized that even clinically healthy domestic sheep or goats can still carry pathogens that are transmissible to wild sheep, and thus, pose a significant risk to wild sheep.

Photo by: Todd Nordeen (NGPC)

Management Recommendations

■ Proportional to risk of association between domestic sheep or goats and wild sheep, land management agencies should work with stakeholders to implement a variety of management practices. Examples include: herders, dogs or other guarding animals trained to repel animals foreign to domestic sheep bands or goat flocks (wandering wild sheep or various predators), regular counts, removal of sick animals, confinement of domestic sheep or goats at night, adequate fencing configurations, covenants, allotment retirements, conversion of class of livestock, trucking versus trailing, and others. Effectiveness of management practices designed to reduce risk of association are not proven (Baumer et al. 2009, Schommer 2009) and therefore should not be solely relied upon to achieve effective separation. Such practices could however, help achieve separation when applied outside of occupied wild sheep range or connected and potentially mitigate impacts associated with straying domestic sheep or goats, or wandering wild sheep.

■ Land management agencies and wildlife agencies should cooperatively manage for quality wild sheep habitat and routinely monitor habitat to detect changes in condition.

■ In areas where association between wild sheep and domestic sheep or goats is likely, land management agencies should post advisory signs at trailheads, campgrounds, and other high-use areas that are designed to educate visitors about the issue of interaction and to encourage prompt reporting of association of wild sheep with domestic sheep or goats. Agencies should also ensure that individuals keep dogs under immediate voice control or on leash to prevent scattering of domestic sheep or goats in permitted areas, or disturbances to wild sheep.

■ Land management agencies should clearly define the processes, protocols, and timelines for short-term or emergency management actions when intervention is needed to minimize risk of association between wild sheep and domestic sheep or goats.

■ Land management agencies should develop programs to foster and recognize the benefits of compliance, cooperation, and cost-sharing in efforts to prevent commingling of wild sheep and domestic sheep or goats on shared ranges.

■ In collaboration with wild sheep management agencies, land management agencies should investigate and implement an option to allow the permittee or producer, or appropriate agency representatives, to remove commingling wild sheep and, where not already established, develop or clarify legal authority for removing stray domestic sheep from public lands by lethal means.

■ Risk assessment should be conducted on an appropriate geographic scale regardless of jurisdictional boundaries. Recognizing the limits of regulatory authority, land management agencies should consider private in-holdings and adjacent private lands when conducting risk assessments.

■ Land management agencies should closely evaluate timing of permitted domestic sheep or goat grazing or trailing activities to reduce risk of disease transmission. For example, grazing estrous domestic females heightens

Photo by: Robin Fehlau (BLM)


Photo by: Stephanie Steinhoff (CPW)

attraction and increases the probability of association between wild sheep and domestic sheep, and should be eliminated where benefits can be accrued.

■ In areas of high risk of association between wild sheep and domestic sheep or goats, agencies and permittees should ensure enhanced monitoring of grazing and trailing patterns using global positioning system (GPS) collars or other technology that provide detailed data on movements and grazing patterns. While enhanced monitoring will not reduce risk of association, it is vital for development of meaningful risk assessments and to ensure appropriate management recommendations are taken to achieve effective separation.

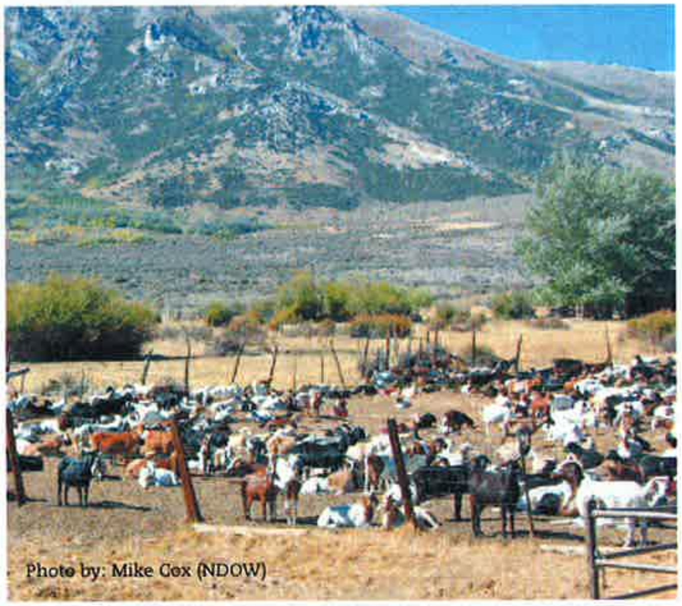


Photo by: Mike Cox (NDOW)

Photo by: Helen Schwantje (BC FLNRO)

RECOMMENDATIONS TO WILD SHEEP AND OTHER CONSERVATION ORGANIZATIONS

■ Recognize and support efforts of wild sheep management agencies and industry leaders in maintaining effective separation.

■ Assist wildlife and land management agencies with development of informational brochures and other materials that identify and explain risk of association between wild sheep and domestic sheep or goats.

■ Assist wildlife and land management agencies with educational efforts regarding risks associated with the use of domestic sheep or goats as pack animals in wild sheep habitat. If use is authorized, encourage participants to closely control, tether, and night-pen their pack stock. Encourage prompt reporting of association between wild sheep and domestic sheep or goats, and promote a reporting system for monitoring association between wild sheep and domestic sheep or goats.

■ Maintain or establish open lines of communication with domestic sheep or goat producers and industry organizations to reduce polarization. Jointly organized and cooperatively-funded workshops on risk assessment, identification of practical strategies to achieve effective separation, development and distribution of pamphlets or brochures, and public speaking opportunities are tangible examples of collaborative, multi-disciplinary approaches to address potential disease transmission.

■ Continue to negotiate alternatives or incentives for domestic sheep or goat permittees to shift their operations to grazing allotments outside of wild sheep habitat. Advocate that permittees convert to a different class of livestock with lower risk of disease transmission or waive permitted domestic sheep or goat use in areas where risk assessment indicates high potential for association with wild sheep.

■ Encourage and support development and funding of cooperative research, and encourage agencies and conservation groups to commit resources necessary to maintain wild sheep populations.

SUGGESTED MANAGEMENT PRACTICES FOR DOMESTIC SHEEP AND GOAT PERMITTEES

The following suggestions are based largely on recommendations provided by CAST (2008), Baumer et al. (2009), or USAHA (2009), and are intended to provide a responsible and common-sense approach for reducing risk of association. However, there is no science-based evidence or evaluation that assesses the effectiveness of these actions to reduce risk or enhance separation (Schommer 2009).

Management Recommendations

■ Implement the following reporting and record keeping procedures or use an existing standard such as the BC (Appendix B) or Wyoming (Appendix C) models:

- Require prompt, accurate reporting by herders working on domestic sheep or goat grazing allotments where association of wild sheep with domestic sheep or goats is possible.
- Support fluency in English or translators for foreign herders in order to facilitate accurate reporting.
- Require sheepherders to use cellular or satellite phones or two-way radios, and location equipment such as GPS receivers to report and record grazing movements and encounters with wild sheep. Seek cost-sharing partnerships for providing communications equipment when an operator changes grazing management practices for the sole purpose of minimizing domestic sheep association with wild sheep. Partnerships could include wildlife management agencies, federal land managers, or private organizations.
- Require herders to record GPS locations, counts, losses and other information in a log book.

■ Place only experienced, informed and responsible sheepherders on allotments located near wild sheep habitat.

■ Ensure that all domestics are individually marked and traceable to source flocks.

■ Conduct full counts when trailing, immediately any time scattering occurs and regularly during general grazing.

■ Develop agreements between permittees and wildlife agencies that provide for locating and reacquiring all stray domestic sheep, either dead or alive. In the event of missing domestic sheep, a comprehensive search should be initiated immediately and the land manager and state wildlife agency must be notified of missing and subsequent recovery of animals.

■ Develop a detection and response protocol that includes:

- Reporting of wild sheep and domestic sheep associations (animal counts and GPS location) to the appropriate wildlife agency.
- Reporting of stray or missing domestic sheep to the land management agency who will, in turn, report that information to the wildlife agency.
- Removal of stray domestic sheep by the permittee, land manager or wildlife agency personnel.
- Removal of individual commingling wild sheep by wildlife agency personnel.
- Collection of standardized diagnostic samples from stray domestic sheep or commingling wild sheep.

■ Utilize the following trailing procedures:

- Conduct full counts when moving on and off each allotment/grazing site.
- Truck domestic sheep through "driveway" areas that pass through occupied wild sheep habitat.
- Truck in water (if needed) to reduce straying.
- Immediately remove animals unable to stay with the flock/herd and move them to a base property.
- Avoid trailing more than 5 miles per day and stop trailing when sheep or lambs show signs of fatigue. Provide for a "babysitter" or removal of lagging sheep when trailing.
- In the event that all animals cannot be accounted for, the permittee must advise the responsible agency and initiate efforts to locate missing animals and implement removal protocol as necessary.

■ Sick domestic sheep should be removed from allotments immediately and must never be abandoned.

Photo by: Mike Pittman (TPWD)

Photo by: Aaron Reid (BC FLNRO)

■ Select herder's camp, nighttime bedding ground, and midday bedding ground locations that maintain communication between guard dogs and herding dogs by smell, sound (barking) and sight, and to take advantage of differences in the sleep cycles of guard dog and herding dogs. Place mature and effective guard dogs and herding dogs with domestic sheep (at least 2 of each per 1000 animals) and do not use female dogs in heat.

■ If grazing on federal lands, comply with established "bed ground" standards. Where conditions permit, construct temporary electric or boundary fences to ensure that domestic sheep remain within selected bedding grounds.

SUGGESTED MANAGEMENT PRACTICES ON PRIVATE LANDS

■ Recognize that domestic sheep or goat farming on private lands can influence wild sheep population viability on adjacent public or other private lands.

■ Report any observed association between wild sheep and domestic sheep or goats on or near private land to the appropriate wildlife conservation agency.

■ Cooperate with wildlife agencies in reporting and removing feral sheep or goats and other exotic bovine ungulates such as aoudad, red sheep, urial, or argali that are detected within or near wild sheep habitat.

■ Participate in cooperative educational efforts to enhance understanding of the issues of disease transmission between domestic sheep or goats and wild sheep.

■ Do not release or leave unattended domestic sheep or goats in areas where they may seek, or be sought, by wild sheep.

■ Cooperate with appropriate agencies, agricultural and producer associations, conservation organizations, and other interested stakeholders to develop effective, comprehensive risk management approaches to help ensure effective separation between wild sheep and domestic sheep or goats, consistent with private property rights in and near wild sheep habitat.
- Possible approaches include, but are not limited to, changing species or class of livestock, purchase of land or the domestic sheep or goats, use of methods to ensure physical separation, or development of conservation incentives, bylaws, covenants, or legislation.

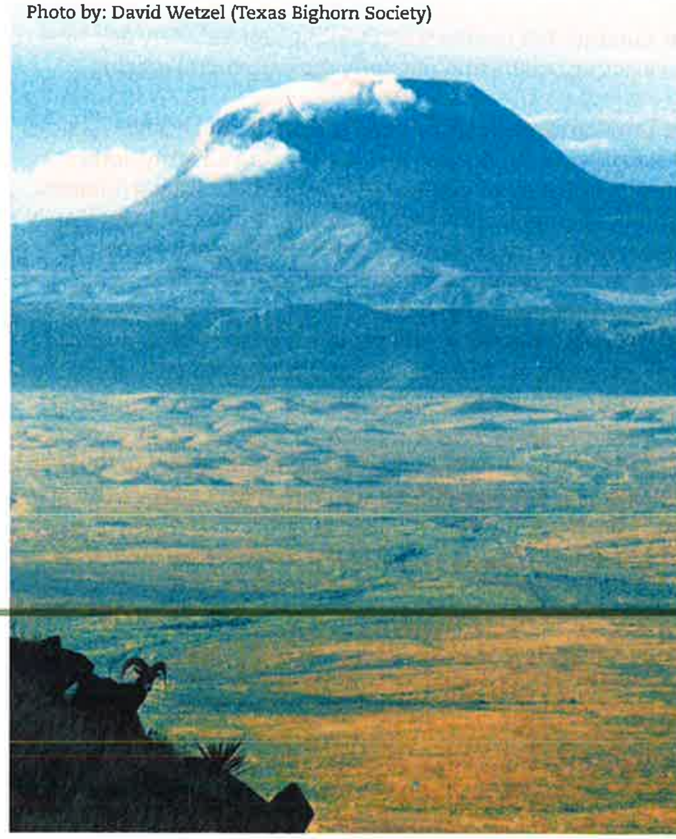
■ Consider partnerships with non-governmental organizations and wild sheep advocate groups for cost sharing on risk management/mitigation strategies such as fencing, or other domestic sheep or goat management actions that reduce risk of disease transmission from private flocks to wild sheep.

■ Support "effective separation" fencing standards that are designed to prevent nose-to-nose contact and aerosol transmission through adequate physical distance, in order to reduce transmission of respiratory disease agents. Examples include: electric outrigger fences (2 feet from page (woven) wire fencing) and double fencing (two page-wire fences with a minimum spacing of at least 10 feet). A combination of fencing methods with or without the use of effective livestock guardian dogs may be most effective to ensure that wild sheep do not physically contact domestic sheep or goats on private land.

■ Participate in or support cooperative research to enhance understanding and test mitigation protocols for disease risk management.

■ Carefully consider the consequences of using domestic sheep or goats for weed control on private lands where association with wild sheep could occur. Work with agencies to develop alternative weed management strategies to reduce risk of association, while adequately managing weed problems.

Photo by: David Wetzel (Texas Bighorn Society)



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Glossary of Terms

Allotment: A portion of a landscape where livestock grazing of a plant community is prescribed according to a specific land use plan or legally defined regulatory authority.

Annual Operating Instructions: Specific language included in a term grazing or trailing permit file; reviewed each year with the permittee, prior to turnout of livestock on a grazing allotment or trailing route.

Association: Close proximity between wild sheep and domestic sheep or goats, potentially leading to direct physical contact and potential disease transmission.

Augment: To intentionally introduce wild sheep from one or more source populations into another existing wild sheep population, to enhance the recipient population demographically or genetically.

Buffer zone: A defined and delineated space on a landscape established by wildlife managers to reduce association and the potential for disease transmission between wild and domestic sheep or goats across that geographic space.

Bighorn sheep: A member of the species *Ovis canadensis* found throughout the mountains of western North America from the Peace River in Canada to northern Mexico and east to the Badlands of the Dakotas.

Contact: Direct contact between body parts of two animals during which a disease might be transmitted from one to another. In this document, "contact" typically refers to nose-to-nose or face-to-face interactions that may lead to the transmission of respiratory disease via secretions or aerosols. Synonymous with "Interaction."

Connectivity: Creating or maintaining networks of habitat that connect fragmented habitats, thus linking population segments of wildlife. Connectivity allows gene flow and enhances long-term species survival.

Conservation Incentives: In direct contrast to regulation-based conservation, incentive-based conservation provides economic, management or esthetic benefits to individuals or corporations to encourage them to conduct management activities that have positive conservation consequence to wildlife or wildlife habitat. Examples are: private land conservation easements, direct lease agreements for grazing rights for conservation purposes, or a trade/exchange of equal value grazing rights among various partners to minimize wildlife-domestic livestock conflict.

Die-off: A large-scale mortality event that impacts many animals from a population and may have significant demographic consequence for the long-term persistence of that population. In this report, such mortality events are usually caused by respiratory disease epidemics involving bacterial or other pathogens alone or in various combinations.

Disease: The word disease means literally "free of ease." Disease is any impairment that modifies or interferes with normal functions of an animal, including responses to environmental factors such as nutrition, toxicants, and climate. Typically, disease involves transmission of, and exposure to, some infectious agent but it may involve non-infectious causes such as congenital defects.

Dispersal: The process whereby individuals leave one habitat or landscape to seek another habitat or landscape in which to live.

Double fencing: Two fences running parallel around a landscape or pasture to prevent contact between animals across the fence line, designed to inhibit disease transmission.

Effective separation: Spatial or temporal separation between wild sheep and domestic sheep or goats, resulting in minimal risk of contact and subsequent transmission of respiratory disease between animal groups.

Feral: An animal of a domestic species that resides in a non-domestic setting and is not presently owned or controlled.

Historic habitat: Based on historic records, landscape that was previously occupied by bighorn sheep and thought to have provided necessary requirements to sustain a wild sheep population through time.

Interaction: Direct contact between body parts of two animals during which a pathogen might be transmitted from one to another. In this document, "interaction" typically refers to nose-to-nose or face-to-face interaction that may lead to the transmission of respiratory disease via secretions or aerosols. Synonymous with "Contact".

Metapopulation: An assemblage of populations, or a system of local populations (demes) connected by movement of individuals (dispersal) among various population segments.

Movement corridor: Routes that facilitate movement of animals between habitat fragments.

Appendix A

Occupied habitat/range: Suitable habitat in which a wild sheep population currently exists.

Preferred: A specific management action that *should* be chosen over another, whenever possible:

Radio collars: Transmitters fitted on neckband material to monitor animal locations.

Global Positioning System (GPS): A radio transmitter fitted on neckband material linked with orbiting satellites; animal locations can be precisely triangulated from space, with the location data then electronically stored in a memory chip or transmitted by various methods for data retrieval.

Very High Frequency (VHF): A radio transmitter fitted to neckband material transmitting in the Very High Frequency range that can be located from the ground or aircraft using a telemetry receiver.

Removal: Physical extraction of domestic sheep or goats, or wild sheep, to eliminate (permanently or temporarily) occupancy of that range or habitat.

Risk/Risk Assessment/Risk Management: In this context, evaluation of the probability that a wild sheep population could experience a disease event with subsequent demographic impacts. Identification of what factors might contribute to the probability of a disease event. Management actions taken to reduce the probability of exposure and/or infection among or between animals. Examples of risk management include separation of infected and non-infected animals, treatment of infected individuals, vaccination, manipulations of the host environment, or manipulations of the host population.

- Qualitative Risk Assessment: Interpretation and analysis of factors that cannot necessarily be measured.

- Quantitative Risk Assessment: Use of tangible data and measurements.

Spatial separation: A defined physical distance between animal populations.

Stray: A domestic sheep or goat physically separated from its flock or band.

Stressor: A specific action or condition that causes an animal to experience stress and the subsequent physiological results of that stress.

Suitable habitat: Landscape that has all necessary habitat requirements to sustain a wild sheep population through time.

Temporal separation: Segregating animal populations over time to prevent association, such that they may occupy the same physical space but at different times.

Thinhorn sheep: A member of the species *Ovis dalli* occurring in Alaska, Yukon Territory, Northwest Territories, and northern British Columbia.

Transmission: The physical transfer (direct or indirect mechanisms) of a disease agent from one animal to another, either within an animal population or between animal populations. In some instances, transmission can lead to full expression of disease in individuals or populations.

Transplant: An intentional movement of wild sheep from a source population to other suitable wild sheep habitat, either currently occupied or not. (Also called "translocation" in some documents.)

Trailing: The planned ambulatory movement of domestic sheep or goats across a landscape or within a corridor to reach a destination where grazing or use will be allowed.

Unoccupied habitat/range: Suitable habitat in which a wild sheep population does not currently exist.

Viability: The demographic and genetic status of an animal population whereby long-term persistence is likely.

Wandering Wild Sheep: Wild sheep, primarily but not always young, sexually-mature rams, occasionally traveling outside of normally anticipated or expected wild sheep range and adjacent habitat. Removal of wandering wild sheep typically does not have population-level implications for wild sheep. Conversely, failure to respond to wandering wild sheep may result in significant, adverse population-level impacts.

British Columbia Domestic-Wild Sheep Separation Project Contact Protocol

The following protocols outline ***the steps to be taken when reports of wild sheep contact with domestic sheep are received by the Ministry of Environment*** in one of several ways:

1. Regular report from public to regional office (Conservation Officer Service or Wildlife Section):

- Contact reported to Regional office.
- Assessment of situation by sheep biologist and COS, in consultation with wildlife veterinarian
- If close contact is confirmed and is considered a high risk situation, consider the following options:
    a. Kill bighorn and save carcass – sample bighorn and/or domestics in consultation with wildlife veterinarian
    b. Continue to monitor bighorn herd in area – observe and record general signs of health
    c. Do nothing – but keep records
- If contact is unsubstantiated/considered low risk, continue to monitor bighorn herd in area, alert and encourage mitigation measures with domestic producers in area to ensure separation.

2. Regular report from public to Call Line.

- Contact reported to Call Line; Call Line staff forwards to regional COS.
- Assessment of situation by COS and sheep biologist, in consultation with wildlife veterinarian
- If close contact is confirmed and is considered a high risk situation, consider the following options:
    a. Kill bighorn and save carcass – sample bighorn and/or domestics in consultation with wildlife veterinarian
    b. Continue to monitor bighorn herd in area – observe and record general signs of health
    c. Do nothing – but keep records
- If contact is unsubstantiated/considered low risk, continue to monitor bighorn herd in area, alert and encourage mitigation measures with domestic producers in area to ensure separation.

3. Out of hours call from public to Call Line.

- Contact reported to Call Line; Call Line staff forwards to regional COS officer-on-call.
- Assessment of situation by COS officer-on-call – contacts sheep biologist and wildlife veterinarian, if possible for consultation
- If sheep biologist and wildlife veterinarian cannot be contacted, biologist and veterinarian will support COS decision and action. COS will inform sheep biologist and wildlife veterinarian by email of the situation and action taken.
- If close contact is confirmed and is considered a high risk situation, consider the following options:
    a. Kill bighorn and save carcass – sample bighorn and/or domestics in consultation with wildlife veterinarian
    b. Continue to monitor bighorn herd in area – observe and record general signs of health
    c. Do nothing – but keep records
- If contact is unsubstantiated/considered low risk, continue to monitor bighorn herd in area, alert and encourage mitigation measures with domestic producers in area to ensure separation.

Appendix C

WYOMING GAME AND FISH DEPARTMENT

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KERRY POWERS

MEMORANDUM

TO: Wildlife Division Employees

FROM: Jay Lawson, Chief, Wildlife Division

COPY TO: Terry Cleveland, Gregg Arthur, File

SUBJECT: **PROTOCOL FOR HANDLING THE COMMINGLING OF BIGHORN SHEEP AND DOMESTIC SHEEP/GOATS**

Due to the threat of disease transmission and subsequent bighorn sheep die-offs, the following protocol should be followed.

Wandering Bighorn Sheep:
Where there is known, suspected, or likely contact by a wandering bighorn sheep with domestic sheep/goats:

- If possible, that bighorn(s) should be live-captured and transported (one-way) to our Sybille Research Unit.
- If that bighorn(s) cannot be live-captured, that bighorn(s) should be lethally removed (per authority of Chapter 56) and, if possible, transported (either whole or samples) to our Sybille Unit or our WGFD Lab in Laramie.

Stray Domestic Sheep/Goat:
Where there is known, suspected, or likely contact by a stray domestic sheep/goat with bighorn sheep:

- The owner of such livestock should be notified and asked to remove the stray sheep/goat to eliminate the threat of disease transmission; however, it will be the owner's prerogative to determine what course of action should be taken.

Reporting:
All documented commingling and any actions taken must be reported to the employee's immediate supervisor, Wildlife Administration as well as the Bighorn Sheep Working Group Chairman, presently Kevin Hurley.

"Conserving Wildlife - Serving People"

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WAFWA

WESTERN ASSOCIATION OF FISH & WILDLIFE AGENCIES

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Washington Department of Fish and Wildlife
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Wyoming Game and Fish Department

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Research Article

Disease, Population Viability, and Recovery of Endangered Sierra Nevada Bighorn Sheep

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ABSTRACT Sierra Nevada bighorn sheep (*Ovis canadensis sierrae*) experienced a severe population decline after European settlement from which they have never recovered; this subspecies was listed as endangered under the United States Endangered Species Act (ESA) in 1999. Recovery of a listed species is accomplished via federally mandated recovery plans with specific population goals. Our main objective was to evaluate the potential impact of disease on the probability of meeting specific population size and persistence goals, as outlined in the Sierra Nevada bighorn sheep recovery plan. We also sought to heuristically evaluate the efficacy of management strategies aimed at reducing disease risk to or impact on modeled bighorn populations. To do this, we constructed a stochastic population projection model incorporating disease dynamics for 3 populations (Langley, Mono, Wheeler) based on data collected from 1980 to 2007. We modeled the dynamics of female bighorns in 4 age classes (lamb, yearling, adult, senescent) under 2 disease scenarios: 5% lower survival across the latter 3 age classes and persistent 65% lower lamb survival (i.e., mild) or 65% reduced survival across all age classes followed by persistent 65% lower lamb survival (i.e., severe). We simulated management strategies designed to mitigate disease risk: reducing the probability of a disease outbreak (to represent a strategy like domestic sheep grazing management) and reducing mortality rate (to represent a strategy that improved survival in the face of introduced disease). Results from our projection model indicated that management strategies need to be population specific. The population with the highest growth rate ($\hat{\lambda}$; Langley; $\hat{\lambda} = 1.13$) was more robust to the effects of disease. By contrast, the population with the lowest growth rate (Mono; $\hat{\lambda} = 1.00$) would require management intervention beyond disease management alone, and the population with a moderate growth rate (Wheeler; $\hat{\lambda} = 1.07$) would require management sufficient to prevent severe disease outbreaks. Because severe outbreaks increased adult mortality, disease can directly reduce the probability of meeting recovery plan goals. Although mild disease outbreaks had minimal direct effects on the populations, they reduced recruitment and the number of individuals available for translocation to other populations, which can indirectly reduce the probability of meeting overall, range-wide minimum population size goals. Based on simulation results, we recommend reducing the probability of outbreak by continuing efforts to manage high-risk (i.e., spatially close) allotments through restricted grazing regimes and stray management to ensure recovery for Wheeler and Mono. Managing bighorn and domestic sheep for geographic separation until Sierra Nevada bighorn sheep achieve recovery objectives would enhance the likelihood of population recovery.

KEY WORDS California, disease, domestic sheep, endangered species management, *Ovis canadensis sierrae*, recovery plan, Sierra Nevada bighorn sheep, Sierra Nevada mountains, stochastic population projection model.

Bighorn sheep (*Ovis canadensis*) populations in North America declined precipitously beginning with European settlement, and the geographic distribution of remaining populations has been greatly reduced (Krausman 2000). Various environmental and demographic factors have been implicated, including unregulated hunting, habitat loss, predation, and diseases introduced by livestock (e.g., Wehausen 1996, Singer et al. 2001). Bighorn sheep are closely related to domestic sheep (*Ovis aries*) and are highly susceptible to certain bacterial infections from them (Onderka and Wishart 1988; Foreyt, 1989, 1994; Lawrence et al. 2010). Today, respiratory disease is one of the greatest obstacles to the

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stability and persistence of bighorn populations in ranges throughout the United States and southern Canada. In particular, bacteria in the genera *Mannheimia*, *Bibersteinia*, and *Pasteurella* (collectively called *Pasteurellaceae*) can cause pneumonia epizootics with high infection rates in wild sheep populations, resulting in all-age die-offs followed by years of depressed reproductive success due to fatal pneumonia in lambs (Foreyt 1990, Coggins and Matthews 1992, Ward et al. 1992, Foreyt 1994). Domestic sheep commonly carry strains of *Pasteurellaceae* that are highly pathogenic in bighorn sheep (Onderka and Wishart 1988; Foreyt, 1989, 1990; Council for Agricultural Science and Technology 2008; Lawrence et al. 2010), and several studies have shown the presence and proximity of domestic sheep to be negatively correlated with bighorn sheep population persistence (Goodson 1982, Gross et al. 2000, Singer et al. 2001, Epps et al. 2004).

The impact of respiratory disease on bighorn sheep populations can vary. Some respiratory pathogens cause illness but not high mortality of adults (hereafter mild outbreaks; Singer et al. 2000, Cassirer and Sinclair 2006). Other respiratory pathogens (especially introduced, leukotoxigenic *Pasteurellaceae* strains) cause catastrophic all-age die-offs with high (>50%) mortality in affected bighorn populations (hereafter severe outbreaks; Foreyt and Jessup 1982, Onderka and Wishart 1984, Coggins and Matthews 1992, George et al. 2008). Whether mild or severe, most respiratory disease outbreaks in bighorn populations are followed by several years of pneumonia caused mortality of lambs resulting in low recruitment rates and juvenile survival (Festa-Bianchet 1988, Coggins and Matthews 1992, Ryder et al. 1994, Jorgenson et al. 1997, George et al. 2008). Continuing lamb infection apparently results from females that remain infective following an outbreak, although mortality or morbidity among the females may not be detectable (Foreyt 1990, Miller et al. 1997, Cassirer and Sinclair 2006). Such recurring lamb infections can substantially delay the recovery of depleted populations to pre-outbreak levels.

Sierra Nevada bighorn sheep (*Ovis canadensis sierrae*) historically occurred along and east of the central and southern Sierra Nevada crest in California (U.S. Fish and Wildlife Service [USFWS] 2007). Unregulated hunting and introduced disease are hypothesized as the cause of the precipitous population decline after European settlement, which left only 2 surviving herds by the 1970s (Wehausen 1980, USFWS 2007). Recovery of the population in one of those areas allowed reestablishment of 3 herds in 3 additional areas through reintroduction, but this was followed by a widespread decline to just over 100 total individuals in the mid 1990s, and the subspecies was listed as endangered in April 1999 (Wehausen 1999, USFWS 2007). Infectious disease is a threat to recovery and persistence of local bighorn sheep populations, although mountain lion (*Puma concolor*) predation may be impacting some Sierra Nevada bighorn populations (Wehausen 1996, USFWS 2007). Several grazing allotments for domestic sheep create risk of pathogen exposure to bighorn sheep populations and continued proximity of domestic sheep to bighorn sheep is considered a risk to recovery efforts (USFWS 2007, Clifford et al. 2009).

The United States Endangered Species Act stipulates that actions on federal lands must not jeopardize the persistence of endangered species (U.S. Endangered Species Act of 1973, 1973). Recovery of endangered species under the Endangered Species Act is accomplished via federally mandated recovery plans that include specific population goals. Our objective was to evaluate the potential influence of introduced respiratory disease on bighorn sheep demography relative to attaining specific population size and persistence criteria outlined in the Sierra Nevada bighorn recovery plan. We also sought to evaluate the effectiveness of hypothetical management strategies aimed at reducing disease risk or impact. To this end, we constructed a stochastic population projection model that incorporated disease dynamics for 3 Sierra Nevada bighorn populations and conducted simulations to evaluate management strategies and estimate probabilities of meeting recovery goals and other demographic outputs. This approach allowed us to heuristically assess the effects of disease on population dynamics, as well as the probability that potential management intervention can assist with meeting recovery plan objectives.

STUDY AREA

The 3 study populations were located on the eastern side of the Sierra Nevada mountain range. The Sierra Nevada extends approximately 650 km along the eastern side of California, ranging from 75 km to 125 km wide (Hill 1975). Climate in the Sierra Nevada is characterized by dry conditions in the warm season (May–Oct), with most of the annual precipitation received as snow in winter (Nov–Apr), which varied considerably by year (Major 1977). There is a strong rain shadow effect in precipitation east of the Sierra crest (Major 1977) resulting in more open, xeric vegetation communities along the lower eastern slope. Low elevations (1,500–2,500 m) were characterized by Great Basin sagebrush (*Artemesia tridentada*) and bitterbrush (*Purshia tridentada*) scrub; middle elevations (2,500–3,300 m) by pinyon (*Pinus monophylla*) woodland, subalpine meadows, and forests; and high elevations (>3,300 m) by sparse alpine vegetation including occasional meadows. Virtually all Sierra Nevada bighorn habitat was public land, managed primarily by Yosemite and Sequoia-Kings Canyon national parks, and Inyo, Humbolt-Toiyabe, and Sierra national forests.

Detailed demographic data were available for each study population, referred to here as the Langley, Wheeler, and Mono populations (Fig. 1) after the main geographic features of their range. The Mono population included the Mt. Warren and Mt. Gibbs herds as defined in the Recovery Plan (USFWS 2007). These discrete local populations were small (<40 females; Johnson et al. 2010*a*) and separated by >50 km of unoccupied habitat. The study populations were known to be geographically isolated; in addition bighorn marked in the 3 study areas with Global Positioning System (GPS; $n = 44$) and very high frequency (VHF) telemetry ($n = 57$) collars for >1 yr showed no movement

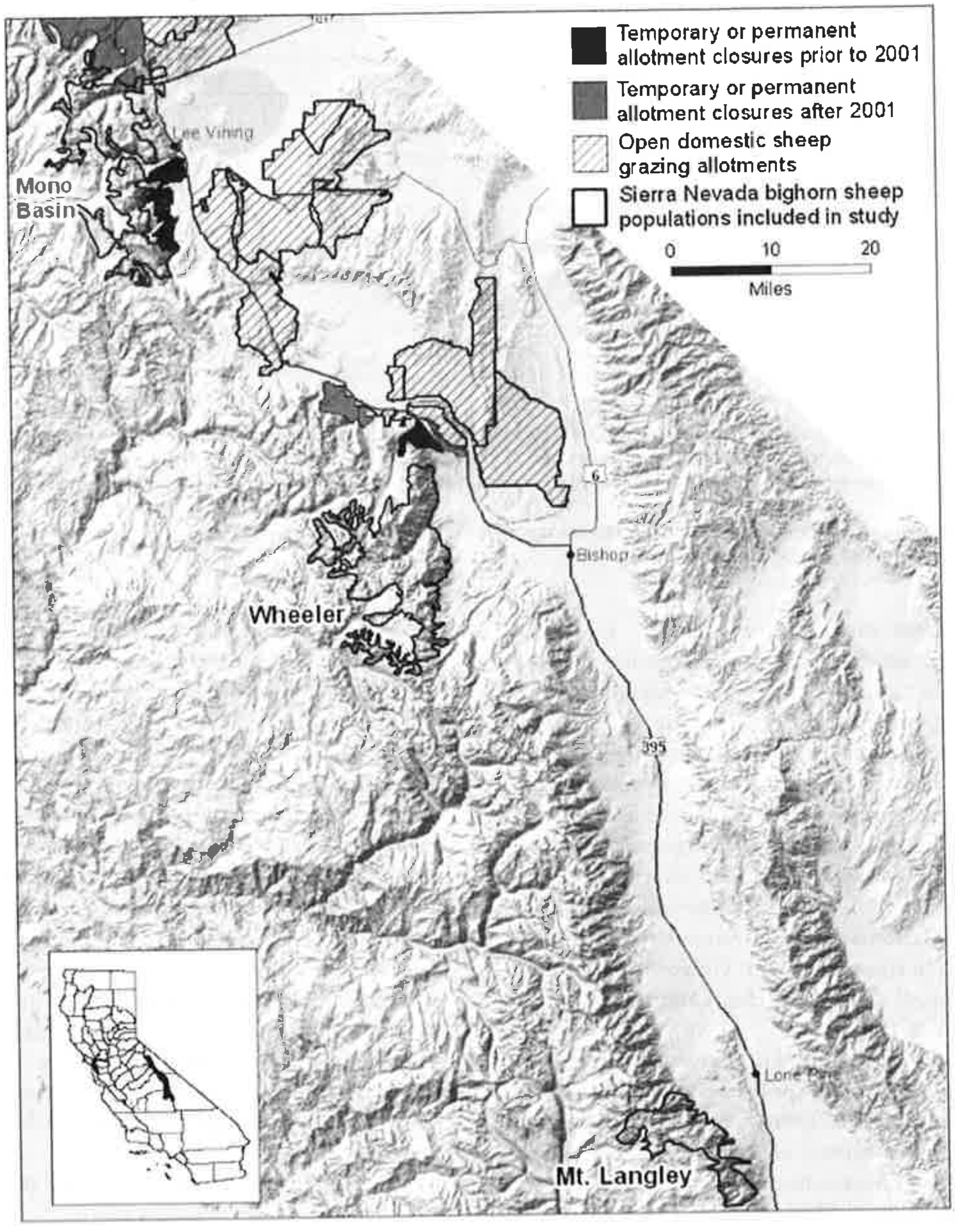

Figure 1. Locations of Langley, Wheeler, and Mono Sierra Nevada bighorn sheep populations and open, temporary, or permanently closed domestic sheep grazing allotments based on data collected 1980–2007 in the Sierra Nevada Mountains, California.

among the study populations. Because the populations were small and did not occupy the entire area considered to be potential habitat, we considered each a single population unit without substructure (i.e., if disease arrives, all individuals in the population would be exposed). No disease-related mortality was documented within the last 35 yr, when intensive research and management activities involving this subspecies were ongoing. Prior collection of field data on this animal was sparse (Wehausen 1980) thus unlikely to detect disease; nevertheless, a die-off of Sierra Nevada bighorn in the Kaweah Peaks in the 1870s was attributed to scabies thought to have been introduced from domestic sheep (Jones 1950). The Wheeler and Mono populations occurred within 8 km straight-line distance from seasonally grazed domestic sheep allotments, whereas the closest allotment to the Langley population was 40 km. We have documented incidences of domestic sheep straying into bighorn sheep habitat and of long-range movements (53 km) made by bighorn males in the Wheeler and Mono areas.

METHODS

Model Parameter Estimation

We based parameter estimates for population models on data collected 1980–2007 (Table 1). Because bighorn sheep are polygynous (Geist 1971), we restricted the model and its parameters to females (Morris and Doak 2002). Annual population surveys for each herd unit included systematic searches for bighorn sheep by experienced observers (see also Johnson et al. 2010*a*). Ground surveys within herd units

Table 1. Number of years of data used for each estimate and estimates used to parameterize population projection models for female Sierra Nevada bighorn sheep based on data collected 1980–2007 in Sierra Nevada Mountains, California.

Population	No. yr	$N(0)$[a]	Corrected mean[b]	Total variance[c]	Process variance
Langley					
Fecundity	11	9	0.331	0.035	0.007
Newborn survival	9	11	0.872	0.024	0.012
Adult survival	9	38	0.977	0.002	0.000
Wheeler					
Recruitment	13	6	0.313	0.022	0.006
Yearling survival	13	4	0.730	0.036	0.014
Adult survival	13	34	0.920	0.010	0.008
Mono					
Fecundity	9	4	0.360	0.007	0.000
Newborn survival	8	3	0.674	0.008	0.000
Adult survival	8	11	0.856	0.024	0.010

[a] $N(0)$ is the starting population vector based on survey data from 2007. For Langley and Mono, $N(0)$ associated with fecundity represents number of lambs, $N(0)$ associated with newborns represents number of yearlings, and $N(0)$ associated with adults represents number of adults, whereas for Wheeler, $N(0)$ associated with recruitment represents number of yearlings, $N(0)$ associated with yearlings represents number of 2-yr-olds, and $N(0)$ associated with adults represents adults.

[b] We corrected parameter estimates with a maximum likelihood approach to remove sampling variance.

[c] Shown for reference; we used process variance in simulations.

occurred over areas ranging from 20 km^2 to 43 km^2. Multiple observers used binoculars and spotting scopes on established routes to completely survey defined habitat. Surveys occurred primarily in open alpine (Jul–Sep) and sagebrush steppe (Jan–Mar) habitats where animals were visible from long distances. Annual surveys provided minimum count data for lambs, yearlings, and adults. However, knowledge of habitat use patterns of each population, intensive monitoring including repeated field efforts when needed, and small (5–35 adult females) observable populations, allowed for annual counts to be near-complete censuses. We surveyed animals in accordance with University of Montana Institutional Animal Care and Use Committee protocol (024–07MHWB–071807).

The annual lambing period for Sierra Nevada bighorn occurs primarily from mid-April through mid-June, and females give birth to 1 offspring/year (Wehausen, 1996, 1980). We conducted surveys of Mono and Langley populations from July to September, just after new lambs were born (post-birth pulse). We conducted surveys of the Wheeler population in late March or early April just before new lambs were born (pre-birth pulse). We observed 3 stage classes during both surveys types; however, the timing of surveys resulted in distinct differences in the data collected that translate to different parameterizations of population projection matrices (Fig. 2; see Johnson et al. 2010*a* for a detailed explanation of age classes for post- and pre-birth pulse surveys).

We used count data of females from successive years to estimate fecundity or recruitment (F post-birth pulse or R pre-birth pulse) and survival (S) values for each life stage on an annual basis (Table 1). For Langley and Mono, populations surveyed post-birth pulse, we estimated fecundity of adult females (F_A), survival from newborn to yearling (S_N), and adult survival (S_A). We estimated fecundity as the number of female lambs/adult females or $N_{N♀}(t)/N_A(t)$. Given the influence of demographic stochasticity inherent with small sample sizes we used available data on the sex of yearlings in year $t+1$ to correct for known numbers of female lambs in year t and assumed a 50:50 sex ratio for lambs of unknown gender. Based on other studies of reproduction of Rocky Mountain bighorns (Gross et al. 2000, Singer et al. 2000, Festa-Bianchet and King 2007) and our pregnancy data for 13 yearlings, we assumed that yearling fecundity was half that of adult females. We estimated newborn to yearling survival as $N_Y(t)/N_N(t-1)$, assuming equal survival between males and females, as we did not identify newborn lambs by sex. We calculated adult female survival as $N_A(t)/[N_A(t-1)+N_Y(t-1)]$. Due to extremely small population sizes in Mono Basin, calculations of adult female survival exceeded 1.0 in 3 yr when we observed 1 (in 1996 and 2002) or 2 (in 2001) additional females in year t than those known to be alive in the previous year $t-1$; we truncated survival in these cases at 1.0. Although field surveys were highly successful at being near-complete

Post-birth pulse (Langley and Mono)

$$\begin{bmatrix} 0 & 0 & F_A S_A \\ S_N & 0 & 0 \\ 0 & S_A & S_A \end{bmatrix}$$

Pre-birth pulse (Wheeler)

$$\begin{bmatrix} 0 & 0 & R_A \\ S_Y & 0 & 0 \\ 0 & S_A & S_A \end{bmatrix}$$

Figure 2. Pre- and post-birth pulse matrix models used to simulate female Sierra Nevada bighorn sheep population dynamics based on data collected 1980–2007 in the Sierra Nevada Mountains, California. Vital rates in the post-birth pulse model are fecundity (F_A), newborn to yearling female survival (S_N), and adult female survival (S_A). Vital Rates in the pre-birth pulse model are recruitment (R_A), 2-yr-old female survival (S_Y), and adult female survival (S_A). Recruitment (R_A) accounts for adult survival.

census counts, these calculations demonstrate error in the data that we account for later.

For the Wheeler population (sampled pre-birth pulse), we estimated recruitment (R_A), survival of yearling to 2-yr old (S_Y), and adult survival (S_A). We calculated recruitment for year t as the number of yearling females/adult females or $N_Y(t)/N_A(t-1)$. We calculated yearling to 2 yr old survival as $N_T(t)/N_Y(t-1)$, where N_T was number of 2-yr-olds, which were an identifiable class in the pre-birth pulse survey. Because this was a pre-birth pulse census, yearlings were still 1–3 months younger than 1-yr-olds and could not consistently be identified by sex in the field. Sex ratio among yearlings was 52% female and 48% male (T. Stephenson, California Department Fish and Game, unpublished data). Consequently, we assumed equal survival between males and females. We calculated adult female survival in year t as $N_A(t)/[N_A(t-1) + N_Y(t-1)]$.

Vital rate estimates included process variance, the true biological variation in a rate due to spatial and temporal factors (often called environmental stochasticity), demographic variance, and sampling variance, arising from inherent uncertainty in parameter estimation (Link and Nichols 1994, White 2000). Because we were only interested in the influence of process variance in vital rate estimates on Sierra Nevada bighorn population performance (White 2000, Mills and Lindberg 2002), we removed sampling (and confounded demographic) variance from our binary vital rate data and report the resulting estimators (Table 1; Burnham et al. 1987, Johnson 1989). We used the program Kendall.m in MATLAB (Morris and Doak 2002) to search >1,000 combinations of means and variances for each rate to estimate corrected population-specific vital rate parameters. We also estimated correlations (positive and negative) among rates for each population (Appendix) using annual vital rate estimates following Morris and Doak (2002). To evaluate if temporal autocorrelation could have induced correlations between vital rates, we estimated the temporal correlation in vital rates for each population using a lag of 1 yr. The results did not show any patterns of significant correlation.

Population Model

For the underlying population model, we constructed a stochastic, discrete time, stage-structured matrix model. Reproduction in our study populations occurred once per year in a short birthing season and adults were capable of reproduction in sequential years. Accordingly, we used a 1-yr (1 May–30 Apr) interval to model population growth. We based our model on 4 approximate life stages—approximate because animals could be 1–3 months older than stated age for post-birth models and 1–3 months younger for the pre-birth pulse model. For post-birth pulse populations, the stages were newborns (*N*; 0–1 yr old), yearlings (*Y*; 1–2 yr old), adults (*A*; 2–16 yr old), and senescent adults (*O*; >16 yr old). For pre-birth pulse populations, the stages were yearlings (*Y*; 1–2 yr old), 2-yr-olds (*T*; 2–3 yr old), adults (*A*; 3–16 yr old), and senescent adults (*O*; >16 yr old).

We included the senescent age class to eliminate accumulation of biologically improbably aged adults that can occur without a terminal stage (Mollet and Cailliet 2002). We estimated the probability that an animal survives the time step and transitions from the adult to senescent age class as (Crouse et al. 1987):

$$p_O = S_A^d\left(\frac{1-S_A}{1-S_A^d}\right)$$

where d is the duration spent in the adult age class for the oldest individuals. We calculated d based on a maximum life expectancy of free-ranging bighorn females of 16 yr (Geist 1971, Jorgenson et al. 1997, McCarty and Miller 1998). We assumed survival of animals in the senescent stage class was zero (Byers 1997). Although differences in survival and reproduction may occur among female adult age classes (McCarty and Miller 1998, Berube et al. 1999, Rubin et al. 2002, Festa-Bianchet and King 2007), available demographic data and current management practices do not allow for further resolution (USFWS 2007).

Because we did not document migration among occupied herd units during 10 yr of intensive study, we did not include immigration or emigration in the model. We tested for density dependence in local populations for the data used in the model (i.e., data collected 1980–2007), using regression analysis of vital rates versus population size (Morris and Doak 2002) and found no evidence of density-dependent effects on stage-specific survival and reproduction. At low numbers the effects of population density on bighorn sheep vital rates may be difficult to quantify (Rubin et al. 2002) and potentially complex relative to theoretical carrying capacity, which may change with habitat use patterns. Under an exponential growth model projected female bighorn population size in the Wheeler and Langley populations grew to untenable levels (e.g., >680 females for Langley by yr 20). Because more recent vital rate data (>2007) suggested density dependency, particularly in reproductive rates (Johnson et al. 2010*b*), we included density dependence in the population model and compared model outputs to a density-independent model.

We incorporated density dependence only in the survival of the youngest class (0–1 yr or 1–2 yr) because bighorn demographic studies have not found density dependence in vital rates of adults (Douglas and Leslie 1986, Wehausen et al. 1987, McCarty and Miller 1998, Festa-Bianchet and King 2007). In addition, long-term studies of large herbivores suggest that adult survival varies little compared to juveniles (Sinclair 1977, Gaillard et al. 1998). For all populations, we used 100 bighorn sheep for carrying capacity for these 3 areas. All 3 areas have had approximately 50 female bighorn (Johnson et al. 2010*a*). We used 100 bighorn sheep for carrying capacity for several reasons. First, from a modeling perspective, the higher the carrying capacity the less density dependent predictions vary from the density independent model for the time frames we used in this analysis. We wished to use the most extreme case, which is the lowest reasonable carrying capacity, to evaluate the case having the greatest divergence with the density independent results. Second, estimates of 100 for carrying capacity were derived in the Recovery Plan (USFWS 2007), based on density dependent patterns of population growth observed in several herds. Finally, because there were large areas of unoccupied habitat in the ranges used by these populations, it was our opinion that the populations could at least double before fill empty habitat.

We used 2 models for density dependence, a Ricker logistic model (Caswell 2001, Morris and Doak 2002) and a ceiling model (Gross et al. 2000, Morris and Doak 2002) in which we invoked the Ricker model of density dependence only after the population size increased to >100 bighorn sheep. For the Ricker model, we solved for the downward survival adjustment parameter so that the populations would grow to 100 by $t = 20$. For the ceiling model, we solved for the downward adjustment parameter such that survival of youngest class at $N = 100$ would yield lambda (λ) = 1 in a deterministic matrix model. We used both forms of the model to explore the potential impact of density dependence on meeting recovery plan goals.

To incorporate environmental variation, we multiplied the population vector for each year by a randomly drawn matrix of vital rate values. We used parametric bootstrapping to select a random value for each vital rate from beta distributions having means, process variances, and a correlation structure specific to each population (Morris and Doak 2002). We generated correlated beta variables by first creating a set of correlated normal random numbers from the vital rates (using Cholesky decomposition), recording their cumulative normal distribution values, and then identifying the numbers (vital rate) from their beta distributions with the same cumulative distribution value (Morris and Doak 2002). Because Sierra Nevada bighorn populations were small, we also incorporated demographic stochasticity in simulations, following Mills and Smouse (1994), for survival and reproduction. We used the randomly selected vital rates in the demographic stochasticity routine to project the population forward. For each model scenario we ran 1,000 iterations and calculated recovery outputs described below. We based the initial population vector on survey data from 2007 (Table 1).

Disease Structure

We incorporated disease by expanding the stage-structured projection matrix in a manner similar to a metapopulation model that includes movement transitions among populations (Morris and Doak 2002). To accomplish this, we expanded the discrete time population matrix to account for demography of individuals within disease states and the flow of individuals between disease states (Oli et al. 2006). Specifically, we embedded a susceptible-infected (SI) disease structure into the matrix by allocating elements to 4 submatrices of the larger matrix to represent populations of susceptible, infected, and transitioning (1 submatrix for susceptible to infected and 1 for infected to susceptible) individuals. The model proceeded in 2 steps: 1) transition in disease status (e.g., susceptible to infected) and 2) survival and, if required, transition to the next stage class.

In addition to vital rate estimates, the combined 4-stage population matrix model with disease (Fig. 3) included the following parameters (for a given yr): $1 - p_O$ = probability of staying in adult class (not becoming senescent), p_I = probability that a susceptible becomes infected between t and $t + 1$, p_S = probability that an infected recovers and becomes susceptible between t and $t + 1$. Each 4×4 submatrix (Fig. 3) represents demography of bighorn in different disease states for each year as: 1) upper left submatrix, those that remained in the susceptible class; 2) upper right matrix, those that transition from infected to susceptible; 3)

$$\begin{bmatrix} 0 & (1-p_I)F_{YS}^{a}S_{AS} & (1-p_I)(1-p_O)F_{AS}S_{AS}^{b} & 0 & 0 & p_S F_{YS}S_{AS} & p_S(1-p_O)F_{AS}S_{AS} & 0 \\ (1-p_I)S_{NS} & 0 & 0 & 0 & p_S S_{NS} & 0 & 0 & 0 \\ 0 & (1-p_I)S_{AS} & (1-p_I)(1-p_O)S_{AS} & 0 & 0 & p_S S_{AS} & p_S(1-p_O)S_{AS} & 0 \\ 0 & 0 & 0^{c} & 0 & 0 & 0 & 0 & 0 \\ 0 & p_I F_{YI}S_{AI} & p_I(1-p_O)F_{AI}S_{AI} & 0 & 0 & (1-p_S)F_{YI}S_{AI} & (1-p_S)(1-p_O)F_{AI}S_{AI} & 0 \\ p_I S_{NI} & 0 & 0 & 0 & (1-p_S)S_{NI} & 0 & 0 & 0 \\ 0 & p_I S_{AI} & p_I(1-p_O)S_{AI} & 0 & 0 & (1-p_S)S_{AI} & (1-p_S)(1-p_O)S_{AI} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} N_{NS} \\ N_{YS} \\ N_{AS} \\ N_{OS} \\ N_{NI} \\ N_{YI} \\ N_{AI} \\ N_{OI} \end{bmatrix}$$

Figure 3. Post-birth pulse disease matrix model for female Sierra Nevada bighorn sheep of the Langley and Mono populations, based on data collected 1980–2007 in the Sierra Nevada Mountains, California. $1 - p_O$ = probability of staying in adult class (not becoming senescent) in a given year, p_I = probability of transitioning from susceptible to infected in a given year, p_S = probability of transitioning from infected to susceptible in a given year, N = newborn (subscript), Y = yearling (subscript), A = adult (subscript), S = susceptible (subscript), I = infected (subscript), and O = senescent (subscript). Subscripts for the vital rate parameters (i.e., F and S) indicate stage class and disease status. For example, F_{AS} represents fecundity of adult susceptibles, the subscript NS represents newborn susceptibles, NI represents newborn infecteds, etc. Yearling fecundity was half that of adult fecundity; $F_Y = 0.5F_A$. For Wheeler, which had a pre-birth pulse survey, we replaced F_{AS} S_{AS} with recruitment rate (R_A; see Fig. 2), which accounts for adult survival, and we replaced newborn survival (S_N) with 2-yr-old survival (S_T). We removed adults that transitioned to the senescent class from the population (essentially they died after transitioning).

lower left matrix, those that transition from susceptible to infected; and 4) the lower right matrix, those that remained in the infected class. We assumed that once an outbreak occurred, all animals transitioned from susceptible to infected (but not all died), that is $p_I = 1$ and $p_S = 0$. Similarly, when the disease course was over, all animals remaining transitioned back to susceptible ($p_S = 1$ and $p_I = 0$).

Although we modeled projections for each population using population-specific demographic parameters (derived from field data), we used a common set of disease and management parameters (derived from field data, data from other outbreaks, and expert opinion) for all populations. We fixed the annual probability of pathogen introduction giving rise to a new respiratory disease outbreak ($p_{outbreak}$) at 0.05 (1 outbreak in 20 yr) to represent a mid-range outbreak probability predicted for grazing practices in the vicinity of the Mono and Wheeler populations (Clifford et al. 2009). Thus, because there was no public grazing near the Langley population, results reflect what could happen if grazing was instituted near that population as well. We modeled all disease outbreaks such that during the first year of an outbreak all age classes were impacted by disease, and for ≥3 subsequent years lamb survival (for pre-birth pulse census this is survival 0–1 yr, whereas for post-birth census this is recruitment) remained reduced (details described below; Coggins and Matthews 1992, Jorgenson et al. 1997, Singer et al. 2000, Cassirer and Sinclair 2006, George et al. 2008). We allowed new outbreaks to overlap; if probability of a new outbreak (i.e., 0.05) was greater than a uniform random number for a given year and a disease outbreak was already in progress, then we reset the year of the outbreak to 1.

We also included reinfection of previously infected individual bighorn sheep in our model to represent the observed sustained effects of some pathogen introductions on bighorn recruitment (Singer et al. 2000, George et al. 2008). Because reinfection appears to primarily reduce recruitment, we only reduced newborn survival (post-birth pulse model) or recruitment (pre-birth pulse model). We modeled the probability of reinfection ($p_{reinfect}$) similarly to the probability of outbreak; that is, if $p_{reinfect}$ was greater than a uniform random number for a given year (given an outbreak was in progress), we reset the year of disease outbreak to 1.

To evaluate the extremes of the potential range of introduced pathogen impacts, we simulated 2 disease scenarios. For the "mild" scenario, we reduced the survival of the 2 older age classes by 5% during the first year to represent a minor respiratory pathogen (Singer et al. 2000, Cassirer and Sinclair 2006). Because Sierra Nevada bighorn have not had exposure for a long period of time, especially compared to Rocky Mountain bighorn sheep, it is likely that disease, if introduced, would be severe and kill a high proportion of the population (Miller 2001, George et al. 2008). Thus, we simulated a severe scenario in which we reduced survival of all age classes by 65% to represent a catastrophic die-off, which is in the range observed in other populations (Onderka and Wishart 1984, Coggins and Matthews 1992, George et al. 2008). For both cases, we decreased newborn survival by 65% during the disease course (Jorgenson et al. 1997, Singer et al. 2000, Cassirer and Sinclair 2006, George et al. 2008). We did not mix mild and severe scenarios in the same model run (i.e., all outbreaks within one run of the model were either mild or severe). We did not model a catastrophic outcome. The results of an extreme outbreak that approached 100% mortality would lead to extinction and therefore we chose not to model it. Although our severe outbreak scenario represented 65% mortality across all age classes, recent outbreaks in wild populations have exceeded 80% (Western Association of Fish and Wildlife Agencies 2007). Indeed, catastrophic mortality following an outbreak would result in extinction of some bighorn herds and severely reduce the likelihood of achieving recovery.

The reported length of disease-related reduced lamb survival varies in free-ranging bighorn from 2 yr to 11 yr (Festa-Bianchet 1988, Coggins and Matthews 1992, Ryder et al. 1994, George et al. 2008) and tends to be longer after catastrophic (≥50%) all-age die-offs (Coggins and Matthews 1992, George et al. 2008) than less dramatic (<50%) outbreaks (Festa-Bianchet 1988, Ryder et al. 1994). We began with ≥2 yr of reduced lamb survival (beyond the first year, in which we reduced survival of all age groups), but to account for variability in the length of disease course and differences between milder and more catastrophic outbreaks, we used different probabilities of reinfection for the 2 scenarios. For the mild-outbreak scenario, we used $p_{reinfect} = 0.10$, which yielded a 27% chance of reinfection during the 3-yr disease course such that 83% of the outbreaks lasted 2–4 yr, 12% for 5–6 yr, and 5% for 7–12 yr (max. = 12 yr). For the severe-outbreak scenario, we used $p_{reinfect} = 0.25$, which yielded a 58% chance of reinfection during the 3-yr disease course such that that 65% of the outbreaks lasted 2–4 yr, 23% for 5–6 yr, and 12% for 7–14 yr (max. = 14 yr).

Management Strategies

We used simulation experiments to assess the potential efficacy of 2 disease management strategies on Sierra Nevada bighorn population dynamics and for meeting recovery plan goals. Management simulations represented current or potential strategies intended to reduce the risks and consequences of disease for Sierra Nevada bighorn sheep (SNBS). We applied each management strategy to the 2 disease models. We reduced the probability of an outbreak ($p_{outbreak}$) to represent a management action that decreases the potential for pathogen introduction (e.g., lowering the probability of contact between domestic and bighorn sheep). We reduced the initial probability of disease outbreak, $p_{outbreak}$, by 50% or 75%, changing it from the baseline simulation of 0.05 to 0.025 or 0.013. These probabilities represent reduced probabilities of outbreak (0.01–0.03) as estimated by Clifford et al. (2009) when domestic sheep grazing was reduced or spatially and temporally managed for separation in the vicinity of the Mono and Wheeler study areas. We compared outcomes to scenarios with no control (0% reduction in $p_{outbreak}$) and complete control (100% reduction).

We also reduced the mortality rate of diseased bighorn to represent a management action that improved bighorn survival in the face of introduced disease (e.g., vaccination). We decreased the mortality rate by 50% or 75% by decreasing disease mortality for all stage classes from 0.65 to 0.325 or 0.1625 for the severe case, respectively, to simulate 2 levels of management efficacy. For the mild case, we only decreased mortality for lambs (to 0.325 or 0.1625) to represent a strategy aimed at enhancing lamb survival and recruitment (Cassirer et al. 2001). For both severe and mild cases, we applied the lower lamb mortality rates in all years where disease depressed lamb survival.

Model Outputs

We performed all simulations with MATLAB 7.7 (The MathWorks, Inc., Natick, MA); we ran 1,000 iterations for each scenario. Although we allowed the models to project population dynamics over 20 yr, we present estimates of all outputs using 5- and 10-yr windows as well. Although 20 yr is useful for heuristic purposes, we considered 5 yr and 10 yr more appropriate time frames during which management plans are likely to be evaluated. To meet recovery, $\geq$12 populations in 4 recovery units must meet recovery goals. We focused on outputs that reflected major recovery plan downlisting or delisting criteria specific to populations (see below), as opposed to land management or regulatory mechanisms (USFWS 2007).

Downlisting (from endangered to threatened status) criterion requires achieving a minimum number of yearling and adult females ($\geq$25 females $\geq$1 yr old) for each population. We calculated the probability that populations achieved downlisting objectives as a probability for each year as the number of simulations in which there were $\geq$25 yearling and adult females divided by the total number of simulations. Delisting (from threatened to recovered status) criterion requires maintaining a minimum number of yearling and adult females ($\geq$25 females $\geq$1 yr old) for $\geq$7 consecutive years for each population. We calculated the probability that delisting targets were achieved as the number of simulations where there was $\geq$1 series of 7 consecutive years in which there were $\geq$25 yearling and adult females by the given output year, divided by the total number of total simulations. Complete delisting further requires that each population is viable with no significant risk of going extinct. We used a quasiextinction threshold of 5 yearling plus adult females for all local populations based on requirements for minimum population size for optimal foraging and antipredator strategies (Berger 1978, Berger and Cunningham 1988). We calculated the probability of quasiextinction for each year as the number of simulations in which the population size was $\leq$5 yearling and adult females divided by the total number of simulations.

We also calculated the time to achieve delisting criteria of having $\geq$25 females $\geq$1 yr old for $\geq$7 consecutive years for each population. We estimated the mean total female population size at each output year and the difference in number of total females between no control and the 2 management strategies (effect size) for the severe disease scenario.

RESULTS

Without disease, the Langley and Wheeler populations grew, whereas the Mono population remained stable (stochastic $\hat{\lambda}_{t=10}$ was 1.13, 1.07, and 1.00, respectively). Including density dependence changed the projected population sizes but did not materially impact recovery outputs at the time scale of importance to management ($\leq$10 yr) for either the discrete logistic model or ceiling model (Table 2). For the $\leq$10-yr time frame, density dependent recovery probabilities were 0–4.5% lower than density independent probabilities, with the only exception being the probability of $\geq$25 sheep under the severe disease scenario (12% lower). Because we did not have compelling evidence for density dependence in our data and because there was little difference between the recovery outputs, we only present results for the simpler density-independent model.

The projected population curves were smooth, in part because all populations were close to their asymptotic stable stage distributions (Johnson et al. 2010*a*). In addition, the process variance on adult survival rates, which had the highest elasticity values for all populations (>0.85; Johnson et al. 2010*a*), was low (Table 1). In the absence of disease, the Langley and Wheeler populations would likely meet delisting criteria within 10 yr, as their estimated probability of quasiextinction was zero and the estimated probability of attaining and maintaining $\geq$25 females for $\geq$7 yr was $\geq$0.96 (Table 3). The Mono population would not likely meet delisting criteria within 10 yr, as the probability of attaining $\geq$25 females was 0.12, and the probability of attaining and maintaining $\geq$25 females for $\geq$7 yr was zero (Table 3).

On average, the Wheeler population performed well with respect to delisting criteria even under mild and severe disease scenarios (Fig. 4A). However, the 95% CI shows that there was a chance of population decline (Fig. 4B). For all populations, if an outbreak occurred, by chance, sooner rather than later, then the population may not grow, as shown by the example simulation trajectories in which an outbreak occurred in year 6 compared to if it happened in year 13 (Fig. 4C). This variation results in the uncertainty reflected in the trajectory CI (Fig. 4B). Under the severe disease scenario, the probability of having a population size $\geq$25 was $\geq$0.88 at the lowest (yr 5), and only in the first 10 yr was the probability <0.90 for attaining and maintaining $\geq$25 females for $\geq$7 yr (Table 3). The Wheeler population would withstand mild disease outbreaks and continue to grow and likely meet delisting criteria (Table 3). However, under the severe outbreak scenario, disease reduced Wheeler's population growth, which made achieving the minimum population size required to delist the species less likely. Although not likely to go extinct, by year 10 the probability of attaining $\geq$25 females was 0.69, and the probability of attaining and maintaining $\geq$25 females for $\geq$7 yr was 0.67 (Table 3). The Mono population would not be likely to recover without management intervention under any disease scenario; the probability of attaining $\geq$25 females was low (0.12 at yr 10 even with no disease), and maintaining that level for 7 yr was $\leq$0.11 for any time frame (Table 3).

Table 2. Projected recovery plan outputs for density independent and density-dependent (DD) models for female Sierra Nevada bighorn sheep of the Wheeler population. We show only Wheeler because it had the largest differences and represents the pattern for all 3 Sierra Nevada bighorn populations. We based population projections on data collected 1980–2007 in the Sierra Nevada Mountains, California.

Disease scenario and pop growth model	Yr	Pr($N < 5$)	Pr($N \geq 25$)[a]	Pr($N \geq 25$) for ≥7 consecutive yr[b]	N
No disease					
No DD	5	0.00	0.98		64
	10	0.00	0.99	0.96	91
	20	0.00	1.00	0.99	186
Full DD[a]	5	0.00	0.99		57
	10	0.00	0.98	0.97	70
	20	0.00	0.99	0.99	98
Ceiling DD[b]	5	0.00	0.99		56
	10	0.00	0.99	0.98	70
	20	0.00	0.99	0.99	93
Mild disease					
No DD	5	0.00	0.96		60
	10	0.00	0.95	0.93	78
	20	0.00	0.97	0.98	131
Full DD	5	0.00	1.00		53
	10	0.00	1.00	1.00	60
	20	0.00	1.00	1.00	75
Ceiling DD	5	0.00	0.98		53
	10	0.00	0.96	0.95	61
	20	0.00	0.96	0.97	74
Severe disease					
No DD	5	0.01	0.78		54
	10	0.05	0.69	0.71	63
	20	0.13	0.65	0.78	87
Full DD	5	0.01	0.75		47
	10	0.06	0.62	0.67	49
	20	0.16	0.54	0.71	47
Ceiling DD	5	0.01	0.78		47
	10	0.06	0.61	0.69	47
	20	0.16	0.53	0.72	46

[a] Full DD represents a discrete time Ricker logistic model with a carrying capacity of 100.
[b] Ceiling DD represents a model in which Ricker model density dependence was invoked only after $N > 100$.

Reducing the probability of outbreak or the mortality rate (which was the same as increasing survival rate) had little impact on reaching recovery plan goals when disease was mild (Fig. 5). Management had different impacts under severe disease scenarios; all results we provided here are for year 10. For Langley, the population with the highest growth rate, management yielded only minor improvements because probabilities of achieving recovery goals were already high (Fig. 5). For Wheeler, management to reduce the odds of disease appeared likely to increase the probability of achieving recovery goals. Decreasing $p_{outbreak}$ or mortality rate by 50% increased the probability of attaining ≥25 adult females by 19% and 33%, respectively; gains in the probability of attaining and maintaining ≥25 adult females were similar (19% and 34%, respectively; Fig. 5). For Langley and Wheeler, management actions had little impact on probability of quasiextinction (Fig. 5). By contrast, for Mono decreasing $p_{outbreak}$ or mortality rate by 50% decreased the probability of quasiextinction by 42% and 54%, respectively, while having little impact on the probabilities of the

Table 3. Projected recovery plan outputs for no disease and disease scenarios for female Sierra Nevada bighorn sheep. For the mild disease scenario, we reduced survival rates of >1-yr-olds by 5% and lamb survival by 65% for the year of disease outbreak. For severe the disease scenario, we reduced all survival rates by 65% for the year of disease outbreak. For both disease scenarios, we reduced lamb survival 65% for 2–14 yr following the first year of disease outbreak. We based population projections on data collected 1980–2007 in Sierra Nevada Mountains, California.

		Pr($N < 5$)[a]			Pr($N \geq 25$)[b]			Pr($N \geq 25$) for ≥7 consecutive yr[b]		
Population	Yr	No	Mild	Severe	No	Mild	Severe	No	Mild	Severe
Langley	5	0.00	0.00	0.00	1.00	1.00	0.88			
	10	0.00	0.00	0.02	1.00	1.00	0.90	1.00	1.00	0.84
	20	0.00	0.00	0.04	1.00	1.00	0.89	1.00	1.00	0.93
Wheeler	5	0.00	0.00	0.01	0.98	0.96	0.76			
	10	0.00	0.00	0.05	0.99	0.95	0.69	0.96	0.93	0.67
	20	0.00	0.00	0.13	1.00	0.97	0.65	0.99	0.98	0.78
Mono	5	0.01	0.02	0.16	0.03	0.02	0.02			
	10	0.04	0.09	0.33	0.12	0.08	0.06	0.00	0.00	0.00
	20	0.13	0.27	0.59	0.20	0.12	0.07	0.11	0.07	0.05

[a] Total female N.
[b] Adult (>1 yr-old) female N.

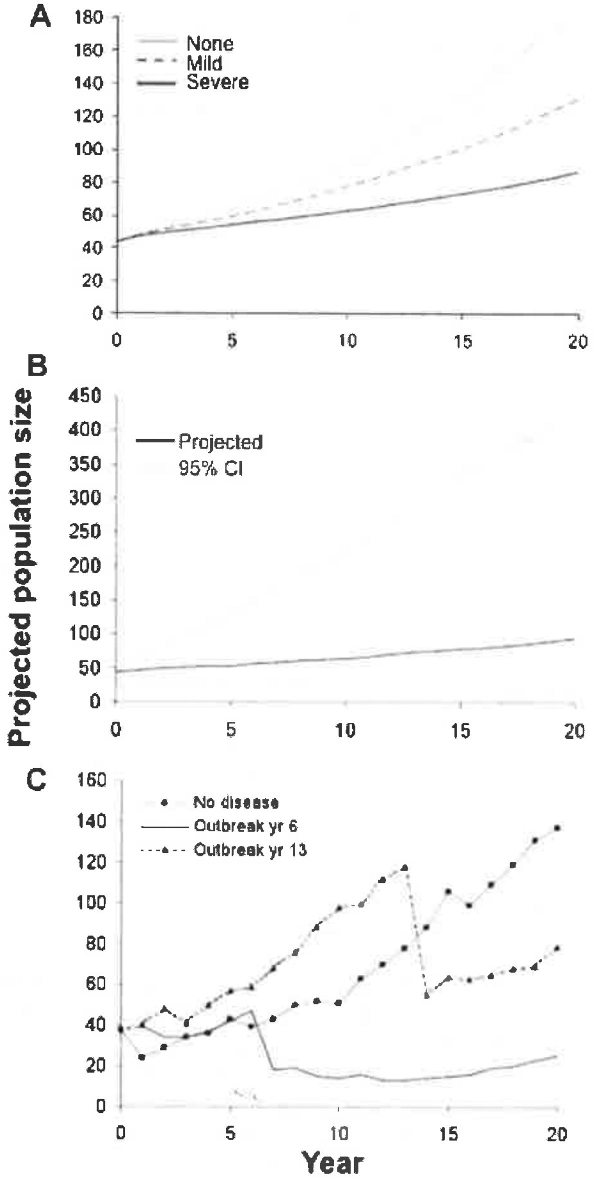

Figure 4. Projected population sizes of female Sierra Nevada bighorn sheep from the stochastic simulation model for Wheeler for (A) mean projected population size for no, mild, and severe disease scenarios, (B) mean projected population size and 95% confidence intervals for severe disease scenario, and (C) single population projections from 3 simulations; one with no disease and two with severe disease outbreaks at different random intervals. We based population projections on data collected 1980–2007 in the Sierra Nevada Mountains, California.

population attaining ≥25 females and of attaining and maintaining ≥25 females (Fig. 5). For all cases, reducing the disease mortality rate had a slightly greater benefit compared to reducing the probability of outbreak by the same percentages (Fig. 5).

The probability that time to recovery was <10 yr for Langley and Wheeler was high (≥0.92) for no disease and mild disease scenarios (Table 4). For the severe disease scenario, probabilities that time to recovery was <10 yr dropped to 0.84 for Langley and 0.66 for Wheeler. More effective management actions (i.e., 75% reductions in probability of outbreak or mortality rate) increased the probability of recovering in <10 yr to ≥0.88 for both populations (Table 4). For Mono, the probability that time to recovery would be ≤10 yr was zero, and the probability of recovering in ≤20 yr was low (≤0.10) for all disease cases and management scenarios (Table 4).

DISCUSSION

Results from our simulations are consistent with previous demonstrations of the negative influence of domestic sheep on bighorn sheep viability (Gross et al. 2000; Singer et al., 2000, 2001). Because population dynamics vary greatly among herds, effective management of Sierra Nevada bighorn requires strategies to be population-specific (Johnson et al. 2010*a*). Simulating respiratory disease in populations and evaluating disease management alternatives underscores this point. The 3 bighorn populations we studied exhibited different population growth rates (Langley $\hat{\lambda} = 1.13$, Wheeler $\hat{\lambda} = 1.07$, and Mono $\hat{\lambda} = 1.00$) and different responses to severe disease. Langley, with its high growth rate, appears robust to disease and may experience milder impacts, whereas Wheeler, with its moderate growth rate, would require disease management to prevent severe outbreaks and meet recovery plan goals. By contrast, Mono, with its flat growth rate, requires management intervention even in the absence of disease to achieve recovery goals. Accordingly, with respect to recovery plan objectives, inference from a nonrepresentative population could lead to incorrect intervention for some Sierra Nevada bighorn populations in the face of a disease outbreak and possibly extinction of some local populations.

Both severe and mild disease outbreaks can increase the time to meet recovery plan goals, although mild disease impacts are less direct. Simulations indicated severe disease can decrease population size and increase time to recovery for all populations, whereas mild disease appeared to have little impact on the recovery of a population. Other field studies have reported population declines only when disease caused increased mortality in all age classes (Coggins and Matthews 1992, Cassirer and Sinclair 2006, George et al. 2008). However, long-term low recruitment rates caused by disease may prevent populations from recovering (George et al. 2008) and, if recruitment is depressed for a long time, the herd may eventually go extinct. A population with a disease outbreak that affected only lamb survival (and hence recruitment), without an initial all-age die-off, will take longer to show a decline than the time span of our simulations, but will still reduce recovery prospects. Moreover, mild disease outbreaks that result in low lamb recruitment reduce the number of surplus animals available for translocation. Recovery of Sierra Nevada bighorn is dependent upon expanding their geographic distribution into historic range via translocations as well as keeping extant herds viable. Even if reduced recruitment does not lead to population declines, it may reduce or end translocation, which is an essential management action to meet recovery goals. Through a reduction in translocation, even a mild disease outbreak can increase the time to achieve the total minimum number of females required for delisting ($n = 305$; USFWS 2007), and hence,

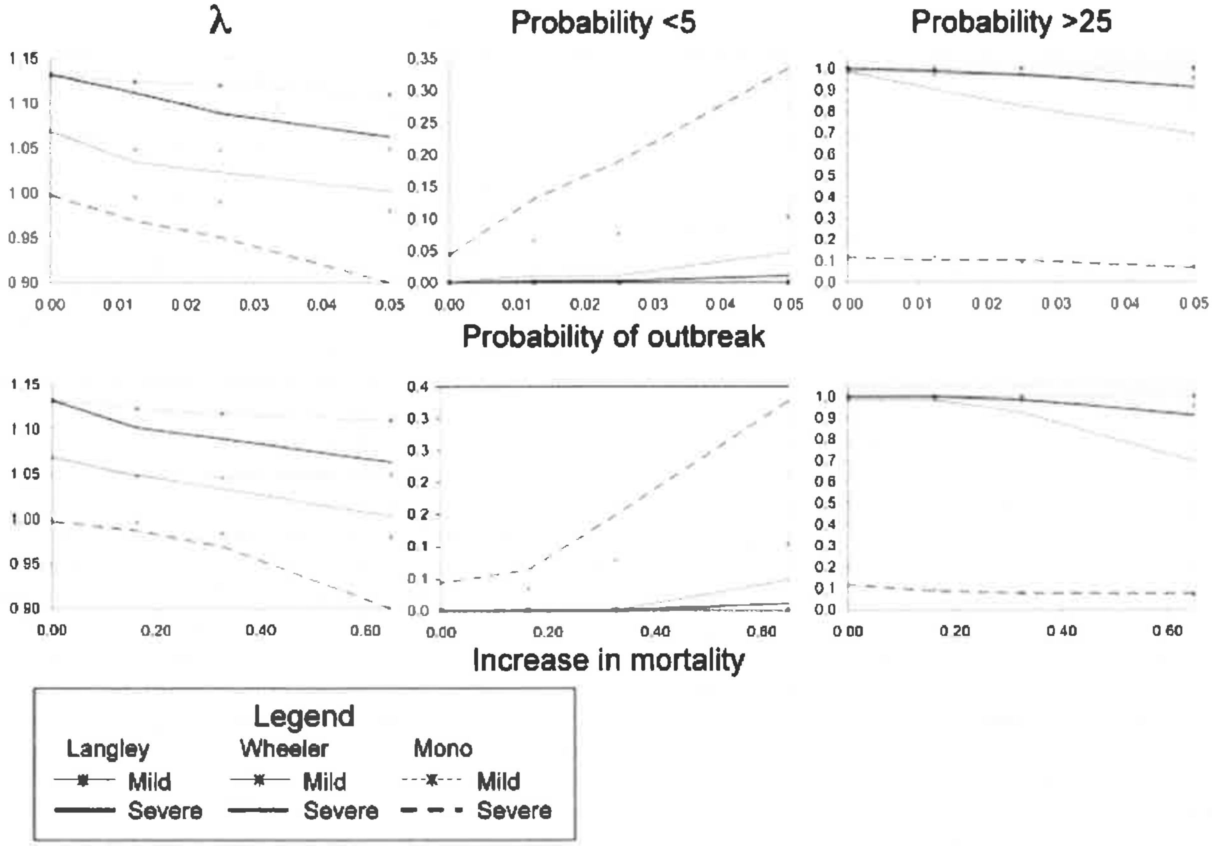

Figure 5. Projected impact of reducing probability of outbreak ($p_{outbreak}$) or mortality rate on recovery plan outputs for year 10 for mild and severe disease outbreaks for female Sierra Nevada bighorn sheep, represented here as the probability that the population falls below <5 females and ≤25 females. The mild disease scenario represents 5% reduced survival across yearling, adult, and senescent age classes and 65% lower lamb survival; severe disease represents 65% reduced survival across all age classes followed by persistent 65% lower lamb survival. We based population projections on data collected 1980–2007 in the Sierra Nevada Mountains, California.

indirectly reduce the overall probability of meeting Sierra Nevada bighorn recovery plan goals over the next 10–20 yr.

Our primary objective was to create a middle-of-the-road disease model to evaluate potential impacts of respiratory disease on Sierra Nevada bighorn population recovery. Because Sierra Nevada bighorn have not had a documented respiratory-disease-related event within 40 yr it is possible that this model underestimates the impact of a disease outbreak on local populations. A respiratory disease outbreak could result in a catastrophic all-age die-off with higher adult mortality than we estimated. For example, catastrophic population losses from respiratory disease of 75% were reported in Idaho (Cassirer et al. 1996) and 80% in Montana (Enk et al. 2001). Moreover, Sierra Nevada bighorn exist in small isolated populations and, therefore, are vulnerable to extinction due to environmental and demographic stochasticity

Table 4. Probabilities of time to recovery for female Sierra Nevada bighorn sheep for different disease scenarios and management strategies. Results shown are for management strategies applied to the severe disease scenario. We based population projections on data collected 1980–2007 in Sierra Nevada Mountains, California.

Population	Time to recovery (yr)[a]	No disease	Mild disease	Severe disease	Pr(outbreak)		Mortality rate	
					50% Reduction	75% Reduction	50% Reduction	75% Reduction
Langley	<10	1.00	1.00	0.84	0.91	0.96	0.98	1.00
	10–20	0.00	0.00	0.08	0.07	0.03	0.01	0.00
	>20	0.00	0.00	0.08	0.02	0.01	0.01	0.00
Wheeler	<10	0.94	0.92	0.66	0.80	0.88	0.89	0.96
	10–20	0.05	0.06	0.10	0.07	0.06	0.07	0.03
	>20	0.01	0.02	0.24	0.13	0.08	0.04	0.01
Mono	<10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	10–20	0.04	0.03	0.02	0.08	0.09	0.06	0.07
	>20	0.96	0.97	0.98	0.92	0.91	0.94	0.93

[a] We define recovery as having ≥25 adult females for ≥7 consecutive years.

alone (Boyce 1992). Even with the severe scenario, an early outbreak could result in more severe consequences than portrayed by the mean population trajectory (Fig. 4). For any severe outbreak, even Langley, the population with the highest growth rate, could face extinction risk or, at a minimum, protracted recovery.

On the other hand, a counterargument can be made that our model overestimates the impact of disease because we did not include any population substructure. That is, if one sheep in the model becomes infected, all sheep in the model become infected and have the same increase in mortality probability. Behavioral or spatial population substructure can serve as a barrier to disease spread by decreasing the chance that one or more groups of sheep contact infected groups (Loehle 1995, Ball et al. 1997, Keeling 1999). Although substructure may exist in the populations we studied, the groups appear to be fission–fusion with mixing on winter range. In addition, male bighorn range far and unpredictably especially during the breeding season (Festa-Bianchet 1986). Fission–fusion substructure combined with male breeding movements are likely to attenuate any barrier effects that substructure can provide for disease spread (Cross et al. 2005, and e.g., George et al. 2008). We conclude that any substructure of Sierra Nevada bighorn is unlikely to influence our general conclusions and that, if anything, we may underestimate the impact a first contact with disease may have on SNBS.

A range of management actions can be employed to diminish disease risk by reducing the probability of outbreak. Disease management strategies include reducing or restricting domestic grazing in the vicinity of bighorn ranges, closely managing domestic sheep for strays, and in some cases, permanently closing allotments or choosing not to convert them to domestic sheep grazing (U.S. Forest Service 2006, Western Association of Fish and Wildlife Agencies 2007, Council for Agricultural Science and Technology 2008, Clifford et al. 2009). Our grazing management simulations reflect these types of actions. Simulation results indicated that reducing the probability of outbreak could increase the probability of meeting recovery goals by 19–34%. A 75% reduction in probability of outbreak would yield high probabilities ($\geq$0.88) of meeting recovery plan goals for all 3 populations within 10 yr. And this size reduction may be attainable; the spatial risk model of Clifford et al. (2009) indicated that current grazing restrictions in the area may reduce the probability of outbreak by approximately 75%.

Although preventing or reducing risk by altering the configuration of grazing allotments is currently the most viable option for management, culling and vaccination are strategies that have been discussed or tested in other bighorn sheep populations (Miller et al. 1997; Cassirer et al. 2001; K. Hurley, Western Association of Fish and Wildlife Agencies, personal communication). We modeled the impact of vaccination, or a similar strategy, to compare this prospective management approach to what is presently used. In addition, we wanted our management simulations to serve a broader purpose as a heuristic tool, with application for other wildlife populations. Simulation results indicated that vaccination was slightly more effective than reducing the probability of outbreak with respect to meeting recovery goals for SNBS. However, the difference was not large enough to be of practical importance. We conclude that preventing disease outbreaks by altering the intensity, location, or duration of domestic sheep grazing remains the most viable and effective management option for mitigating disease risk.

Stochastic projection models are well recognized for their ability to synthesize data, identify data gaps, identify sensitive vital rates to target for management, and evaluate different population scenarios (e.g., varying predation rates, severe weather) and management actions (e.g., removals for translocations, habitat enhancements; e.g., Beissinger and Westphal 1998, Morris and Doak 2002). In the context of endangered species management, stochastic projection models are especially useful because they allow managers to develop a realistic assessment of the probability of meeting recovery plan goals and can be employed when a population's small size or status precludes experimentation. The addition of disease to such models is important. First, this approach explicitly addresses how disease can influence demographic properties and structure of populations (Cunningham and Daszak 1998). Second, it can help managers to evaluate the effect of multiple disease management strategies on population performance, as well as recovery and extinction probabilities.

Our approach to modeling disease outbreaks was an extension from similar models (Haydon et al. 2002, Oli et al. 2006), and provides a more realistic approach to modeling infection and reinfection of a certain class or classes. The model's inputs can be easily modified to represent other diseases with different probabilities of infection, lengths of infectivity, probabilities of reinfection, mortality rates, etc. In addition, model inputs include annual additions and subtractions of animals to allow managers to evaluate the impact of disease with different levels of predation and translocation (see Supporting Material available online at www.onlinelibrary.wiley.com). We hope this model provides an accessible flexible framework for incorporating disease in stochastic population projection modeling and will serve as a useful tool for other ungulate managers. The ability to generalize this model reflects our intent to provide a framework that will stimulate discussion and research leading to improvements on existing methodology and ungulate conservation.

MANAGEMENT IMPLICATIONS

Our simulation results indicate that management strategies for Sierra Nevada bighorn need to be population specific. Based on our findings, we recommend that multiple representative populations be monitored as part of any endangered species recovery and monitoring plan. Our stochastic population model supports Sierra Nevada bighorn recovery efforts because it allows managers to evaluate the probability of meeting recovery goals in light of disease risk. In general, we recommend that stochastic population models used for endangered species management include outputs cast as probabilities of meeting recovery plan goals. The risk of disease outbreaks for SNBS, whether mild or severe, must be mitigated to increase the probability of meeting recovery plan goals. That is, simulations indicate that severe outbreaks decrease population sizes and directly reduce the probability of meeting minimum population size goals, whereas mild outbreaks reduce recruitment and the number of individuals available for translocation to other populations and indirectly reduce the probability of meeting overall, range-wide minimum population size goals. Moreover, because it is possible that our model underestimates the impact disease will have on Sierra Nevada bighorn recovery, continued reduction of the risk of disease outbreak is paramount. At a minimum, to assist recovery for the Wheeler and Mono populations we recommend reducing the probability of outbreak by continuing efforts to manage high-risk (i.e., spatially close) allotments through restricted grazing regimes and stray management. We also recognize that closing grazing allotments until Sierra Nevada bighorn achieves recovery objectives would further population recovery. As managers consider reintroduction of wild sheep throughout the western United States, it is important that they determine the level of disease risk and consequences of outbreaks and evaluate potential management strategies.

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Appendix. Correlation matrices for Sierra Nevada bighorn sheep population vital rates based on data collected 1980–2007 in Sierra Nevada Mountains, California.

Population	Recruitment or fecundity	2-yr-old or yearling survival	Adult survival
Wheeler			
Recruitment	1.0		
2-yr-old survival	0.442	1.0	
Adult survival	0.262	0.696	1.0
Langley			
Fecundity	1.0		
Yearling survival	−0.127	1.0	
Adult survival	−0.172	−0.263	1.0
Mono			
Fecundity	1.0		
Yearling survival	−0.185	1.0	
Adult survival	−0.337	0.096	1.0

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A Review of Disease Related Conflicts Between Domestic Sheep and Goats and Bighorn Sheep

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Timothy J. Schommer
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Abstract

Research shows that contact between bighorn sheep and domestic sheep and goats can lead to respiratory disease and fatal pneumonia in bighorn sheep. We reviewed experimental methods and evidence regarding respiratory disease in bighorn sheep relative to domestic sheep and goats based upon the contact hypothesis and categorized by experimental approach. Although efforts to identify organisms causing pneumonia in bighorn sheep following contact with domestic sheep have identified multiple bacteria species, the complete range of mechanisms/causal agents leading to epizootic disease events are not completely understood. However, based upon the effect of disease transmission, spatial and/or temporal separation between domestic sheep and goats and bighorn sheep is prudent when the management objective is to maintain bighorn sheep populations.

Keywords: *Ovis*, *Capra*, respiratory, disease, transmission

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Contents

A Review of Disease Related Conflicts Between Domestic Sheep and Goats and Bighorn Sheep

Timothy J. Schommer
Melanie M. Woolever

Introduction

The purposes of this document are to: 1) review the science related to disease, particularly respiratory disease, in sympatric populations of domestic sheep (*Ovis aries*) and goats (*Capra hircus*) and bighorn sheep (*Ovis canadensis*) and 2) provide scientific foundation for the development of agency policy. For the purpose of this document, the terms pneumonia and respiratory disease are used interchangeably as are the terms bighorn sheep, wild sheep, and mountain sheep. Additionally, the organism called *Pasturella haemolytica* has been renamed *Mannheimia haemolytica*, but because much of the scientific literature uses the old nomenclature, the names should be considered synonymous.

Major bighorn sheep die-offs have been reported from the mid-1800s to present and have been known to occur in every western state (Martin and others 1996; Toweill and Geist 1999). Research shows that contact between bighorn and domestic sheep can lead to respiratory disease and fatal pneumonia in bighorns (Callan and others 1991; Foreyt 1989, 1992a, 1994; Foreyt and Lagerquist 1996; George and others 2008; Onderka and Wishart 1988). Therefore, the role that domestic sheep play in causing pneumonia in bighorn sheep is an important issue in multiple-use management (Foreyt and others 1994; Hurley 1999; Schommer and Woolever 2001; Schwantje and others 2006).

Presently, about 90 percent of Rocky Mountain bighorn sheep (*Ovis canadensis canadensis*) and 20 percent of desert bighorn sheep (*Ovis canadensis nelson*) in the United States spend all or part of their lives on National Forest System lands. Although domestic sheep allotments on national forests in the western United States have declined greatly in number, they remain numerous in some areas. When domestic and wild sheep ranges overlap or are in close proximity, bighorn sheep advocates, whether from state agencies, non-governmental organizations, or tribes, express concern regarding the potential for contact between the species. Managers often struggle because they lack an understanding of the disease-related conflicts between domestic sheep and goats and bighorn sheep, or of how to develop potential solutions. An earlier document by Schommer and Woolever (2001) provided management guidance for national forests supporting bighorn sheep populations and this document has proven effective in aiding in the development of solutions across the western United States.

History

The original distribution of native sheep in North America extended north to the Brooks Range in Alaska, south to Baja California and the northern reaches of mainland Mexico, and east to western Texas and the badland and river break habitats immediately east of the Rocky Mountains in North and South Dakota and western Nebraska (Buechner 1960; Valdez and Krausman 1999). It is usually assumed that all suitable habitats were historically occupied.

The distribution of native sheep in Alaska and Canada remains essentially unchanged (Valdez and Krausman 1999). In contrast, many populations to the south have gone extinct, including all native populations in Washington, Oregon, and neighboring regions of southwestern Idaho, northeastern Califorinia, and northwestern Nevada (Buechner 1960). Toweill and Geist (1999) reported bighorn sheep extirpations from Arizona, New Mexico, Nebraska, Nevada, North Dakota, South Dakota, Utah, Oregon, and Washington. The states of California and Nevada lost an estimated 110 native populations (McQuivey 1978; Wehausen and others 1987; Wehausen and others in prep). Desert bighorn sheep were extirpated from the states of Coahuila, Chihuahua, and Nuevo Leon, Mexico and Colorado and Texas, USA. Populations in other western states of the United States and Mexico probably declined to less than 5,000 individuals (Toweill and Geist 1999). Although estimates of historical bighorn sheep numbers in pre-Columbian North America have been debated (Buechner 1960; Seton 1929; Valdez 1988), there is general consensus that population estimates of the Twentieth century are comparatively lower (Buechner 1960; Toweill and Geist 1999; Valdez and Krausman 1999).

Bighorn sheep recovery began during the 1960s in most western states and has continued to the present. State wildlife agencies have ongoing efforts in partnership with land management agencies that include transplanting sheep into unoccupied habitat, augmenting existing herds, and manipulating habitat. While success rates vary, herds found at peak population or in close proximity to domestic sheep tend to be more susceptible to die-offs (Monello and others 2001). Since most western state agencies have a policy of not re-establishing bighorns near domestic sheep operations, recovery of bighorn sheep into those vacant habitats is probably being limited. Even with the ongoing recovery efforts, current bighorn sheep numbers in the western United States are only a fraction of their original numbers. In 1999, Toweill and Geist estimated the population of all species in the contiguous United States at about 47,900 individuals, far fewer than historical estimates proposed by Seton (1929) and Buechner (1960).

Widespread bighorn sheep extirpations in North America are geographically coincident with regions where historically large numbers of domestic sheep grazed (Wehausen and others in prep). Researchers have long hypothesized that disease transferred from domestic sheep was a key factor in the widespread loss of bighorn sheep populations (Valdez and Krausman 1999; Wehausen and others in prep). For example, the first large-scale population losses in the nineteenth century were principally attributed to scabies introduced by domestic sheep. This conclusion was based largely on clinical evidence of scabies in bighorn sheep during die-offs and the fact that these scabies outbreaks closely followed the introduction of domestic sheep (Buechner 1960; Honess and Frost 1942; Jones 1950; Smith 1954). Further negative correlations between the presence of domestic sheep grazing and the health of bighorn sheep populations emerged in the

Twentieth century (Wehausen and others in prep). In Nevada, McQuivey (1978) noted a negative correlation between past domestic sheep grazing and the persistence of bighorn sheep populations. Additionally, an accumulation of considerable circumstantial evidence supports the hypothesis that bighorn sheep die-offs frequently follow contact with domestic sheep (Cassirer and others 1996; Coggins 1988, 2002; Foreyt and Jessup 1982; Goodson 1982; Martin and others 1996; Singer and others 2001). Finally, Monello and others (2001) concluded that bighorn herds are rendered vulnerable to pneumonia transmission of *Pasteurella* spp. from domestic sheep serving as reservoir hosts.

Although respiratory disease resulting in pneumonia is the most serious and devastating disease at a population level that is shared by domestic and bighorn sheep, other diseases and parasites, including but not limited to scabies, anaplasma, babesia, ovine parapox (contagious ecthyma), and infectious keratoconjunctivitis (pink eye), may be communicable (Jessup and Boyce 1993).

Disease Review

An understanding of the disease-related conflicts between domestic sheep and goats and bighorn sheep is essential to the development of agency policy regarding management of these species.

Research concerning disease transmission when bighorn sheep come into contact with domestic sheep has been extensive over the past quarter century. The hypothesis that contact with domestic sheep results in pneumonia in bighorn sheep has been researched under a variety of experimental conditions. The following is a review and summary of the experimental methods and evidence relative to the hypothesis that bighorn sheep have a high likelihood of contracting fatal respiratory disease following contact with domestic sheep, characterized as the "contact hypothesis" (Wehausen and others in prep). Additional hypotheses that are refinements of the contact hypothesis are addressed (Wehausen and others in prep). The following summary of this information is categorized by experimental condition: 1) unplanned pen experiments; 2) planned pen experiments; 3) planned pen experiments with other species; 4) inoculation experiments; 5) research to identify bacteria strains causing fatal pneumonia; and 6) vaccination trials. A seventh section includes other pertinent disease information. A brief review of science panel conclusions follows the summary.

Unplanned Pen Experiments

The contact hypothesis has been tested numerous times in captive situations. Two tests were accidental in nature and, therefore, lacked any experimental design. However, because of the information garnered from those captivity situations, they still serve as tests of the contact hypothesis. One of the unplanned experiments occurred at Lava Beds National Monument, where a population of bighorn sheep was established in 1971 in a 5.4 km^2 enclosure (Blaisdell 1972). In 1980, nose-to-nose contact was observed through the enclosure fence between bighorn sheep and domestic sheep grazed on adjacent National Forest System lands. Bighorn sheep began dying of pneumonia 2 to 3 weeks later, and all 43 bighorn subsequently died (Foreyt and Jessup 1982). The second situation involved bighorn sheep in Washington that had been in a 2.5 ha enclosure for 10 months when domestic sheep were added to the pen. Thirteen of 14 bighorn sheep died within 8 weeks of interspecies contact (Foreyt and Jessup 1982).

Planned Pen Experiments

Following the unplanned experiments, three independent research groups conducted 10 experiments designed to test the contact hypothesis using one to six captive bighorn sheep per trial. Five of these experiments used only domestic sheep (Foreyt 1989, 1990, 1994; Onderka and Wishart 1988) while contact in the other five (Callan and others 1991) involved a mixed flock of domestic sheep and hybrids of argali (*Ovis ammon*) and mouflon (*Ovis musimon*) sheep, the latter of which is the source of domestic sheep (Ramey 2000). The latter five trials also included treatments that attempted to control the resulting pneumonia in the bighorn sheep. All 23 bighorn sheep tested in these 10 trials died of respiratory disease following contact with domestic sheep or were euthanized when close to death. In every case, all the domestic and hybrid sheep remained healthy.

Two basic mechanisms have been hypothesized to explain the planned pen results: 1) contact results in transmission of microbes from domestic sheep to bighorn sheep that directly or indirectly leads to fatal pneumonia in the latter species and 2) introduction of another species into the pen creates a psychological effect on the bighorn sheep that results in a stress-related, compromised immune system that leads to respiratory disease unrelated to the transmission of different microbes (Wehausen and others in prep).

Planned Pen Experiments With Other Species

Planned pen experiments that put captive bighorn sheep in contact with other species do not support the stress hypothesis. Foreyt (1992a, 1994) and Foreyt and Lagerquist (1996) conducted eight independent contact experiments involving bighorn sheep penned with: 1) elk, white-tailed deer, and mule deer; 2) elk alone; 3) domestic goats; 4) mountain goats; 5) llamas; 6) cattle; 7) horses; and 8) steers. Of the 39 bighorn sheep tested in these experiments, only two died. One was an old female whose death was most likely due to a tooth abnormality that adversely affected her feeding ability. The other death was a bighorn sheep in the pen with the steers that died of pneumonia (Foreyt and Lagerquist 1996). These findings suggest that the presence of other species in pens itself is unlikely to lead to bighorn sheep deaths and that species other than domestic sheep are considerably less likely to transmit microbes fatal to bighorn sheep. This latter conclusion is consistent with a lack of historical observations or circumstantial data linking such species to bighorn sheep die-offs.

Recently, however, domestic goats have been implicated in fatal disease transmission to bighorn sheep. Some goats carry *Mannheimia* and *Pasteurella* species that have been identified in bighorn sheep disease events. DNA analysis conducted during a 1995 to 1996 Hells Canyon bighorn die-off revealed that a feral goat and two bighorn sheep shared a genetically identical *P. multocida* and *M. haemolytica* (Rudolph and others 2003; Weiser and others 2003). Since that time, other incidents involving domestic goats and bighorn sheep have been documented. An infectious keratoconjunctivitis (IKC) epizootic in bighorn sheep occurred in the Silver Bell Mountains, Arizona, in 2003 and 2004 (Heffelfinger 2004). That bighorn sheep population had been monitored for several decades prior to the incident, without evidence of IKC. Genetic investigation strongly suggests that domestic goats transmitted IKC to native bighorn sheep (Jansen and others 2006). Contagious ecthyma was also transmitted to the previously native bighorn sheep in the same incident.

Inoculation Experiments

The hypothesis that specific strains of pneumophilic bacteria frequently carried by healthy domestic sheep are the cause of fatal pneumonia in bighorn sheep following contact between these species (Goodson 1982; Wehausen and others in prep) has been tested. In these experiments, captive bighorn sheep were inoculated with bacteria cultured from the respiratory tracts of domestic sheep. Both accidental and planned experiments have had similar results. The accidental experiment occurred when a lavage tube used to sample lung cells of domestic sheep was not fully sterilized before being used to obtain lung cultures from three captive bighorn sheep. Of the 10 original bighorn sheep in the herd, three died of pneumonia, as did three more bighorn sheep added to this herd during that time period (Foreyt 1990).

The planned inoculation experiments comprised six independent trials carried out by two different research groups using *Mannheimia haemolytica* cultures from domestic sheep (Foreyt and others 1994; Foreyt and Silflow 1996; Onderka and others 1988). Of the 13 bighorn sheep inoculated with those bacteria, 12 died of acute bronchopneumonia. Two groups of control bighorn sheep (five total) remained healthy, as did two groups of domestic sheep (nine total) that received the same inoculation doses as the bighorn sheep. Two of these inoculation trials (Foreyt and Silflow 1996; Onderka and others 1988) included experiments in which the source of the *M. haemolytica* inoculum was from healthy bighorn sheep. The three bighorn sheep used in the two trials showed no clinical signs of disease after the inoculations, nor did the seven domestic sheep similarly inoculated.

Foreyt and others (1996) also carried out an inoculation trial of three Dall's sheep (*Ovis dalli dalli*). Two of these sheep received a *Mannheimia haemolytica* strain (A2) from domestic sheep that was known to be fatal to bighorn sheep, while the other received a strain not considered pathogenic. The sheep receiving the non-pathogenic strain remained healthy. The other two developed bronchopneumonia and one died and the other was euthanized prior to death.

Research to Identify Microbial Strains Causing Fatal Pneumonia

The results of the various contact and inoculation trials support the occurrence of microbial transmission (Wehausen and others in prep). With sufficient diagnostic tools, it should be possible to identify the specific microbe(s) that causes fatal pneumonia in bighorn sheep. However, the goal of identifying all specific pathogenic organisms has proven elusive (Rudolph and others 2007; Wehausen and others in prep). First, multiple bacterial species have been implicated as disease agents. While *Mannheimia haemolytica* (especially the A2 strain) has been cultured from many bighorn sheep dying of pneumonia following experimental contact with domestic sheep, one set of experiments attributed the deaths to *Pasturella multicida* (Callan and others 1991). Additionally, some strains of *M. haemolytica* are now recognized as a separate species, *P. trehalosi*. Second, traditional methods used to differentiate strains of *M. haemolytica* by biotypes and serotypes (Dunbar and others 1990a,b; Queen and others 1994) have lacked adequate resolution. Previously undescribed serotyopes have been found in bighorn sheep (Dunbar and others 1990a) while other strains could not be identified using these methods (Dunbar 1990a; Silflow and others 1994; Sweeney and others 1994; Ward and others 1997), rendering these classification methods unsatisfactory for epidemiological investigations of this phenomenon (Jaworski and others 1993).

To overcome limitations of traditional methods, additional diagnostic tools have been applied to *Mannheimia haemolytica* and *Pasturella trehalosi* in attempts to identify strains responsible for bighorn sheep deaths. These methods include: 1) binary classification as hemolytic or non-hemolytic (Ward and others 2002; Wild and Miller 1991, 1994); 2) variation in surface proteins (Ward and others 1990); 3) assays of toxicity relative to peripheral neutrophils (Silflow and others 1993; Silflow and Foreyt 1994; Sweeney and others 1994); 4) DNA fingerprinting to identify different genetic forms (Foreyt and others 1994; Jaworski and others 1993; Snipes and others 1992; Ward and others 1997; Weiser and others 2003); and 5) culture-independent PCR-based methods and sequence-based phylogenetic analyses of multiple DNA loci (Kelley and others 2006; Safaee and others 2006). While DNA fingerprinting has been useful for investigating the transmission of bacterial strains between different species and individuals (Ward and others 1997), all of the above five methods appear to lack predictive power relative to identifying strains involved in fatal pneumonia in bighorn sheep.

Vaccination Trials

Vaccinations have been investigated as a potential solution but are not viewed as a viable management option for bighorn sheep. First, vaccination would be required annually and second, the difficulty vaccinating wildlife is exacerbated by the steep rocky terrain that bighorn sheep inhabit.

Ward and others (1999) investigated immunologic responses of bighorn and domestic sheep to a vaccine for three strains of *Mannheimia haemolytica*. They found that the vaccine produced only a moderate and transient immunologic response. Miller and others (1997) and Kraabel and others (1998) tested a vaccine for three different *M. haemolytica* strains on captive bighorn sheep. The sheep were challenged with a *Pasturella trehalosi* vaccine cultured from the lungs of free-ranging bighorn sheep during a pasteurellosis epizootic. Control and vaccinated bighorn both developed acute pneumonia, but the vaccinated bighorn sheep experienced lower mortality (30 versus 80 percent).

Cassirer and others (2001) conducted experiments with free-ranging and captive bighorn sheep to test the efficacy of vaccines against *Mannheimia* spp. and *Pasteurella* spp. to reduce mortality of adults and lambs. Vaccinated females suffered notably higher lamb mortality.

Only two vaccination trials have used strains of *Mannheimia haemolytica* derived from domestic sheep as the post-vaccination challenge. Foreyt and Silflow (1996) inoculated two bighorn sheep twice with a non-lethal cytotoxic strain of *M. haemolytica*, and 6 weeks later, they inoculated them with a lethal cytotoxic strain (A2) from domestic sheep. The non-lethal strain provided no significant protection, and both bighorn sheep died of pneumonia. Foreyt (1992b) tested an experimental bacterin-toxoid vaccine for three *M. haemolytica* strains, using three treatment and three control bighorn sheep. After contact with domestic sheep, five of the six bighorn sheep, including the three vaccinated, died of pneumonia. There was no evidence of any protection from the vaccine.

Other Pertinent Disease Information

Microbial Transmissibility

Although malnutrition, harsh weather, and other stressors may exacerbate susceptibility to disease, viruses, parasites, and bacteria can weaken or kill bighorn sheep. Bacteria, primarily *Mannheimia* spp. and *Pasteurella* spp., have led to massive, all-age die-offs of bighorn sheep in every western state (Martin and others 1996) and have been reported as the primary cause of bighorn sheep population declines throughout North America (Hurley 1999; Schwantje 1988; Wehausen and others in prep). Of the numerous pathogens affecting bighorn sheep, *M. haemolytica* has been viewed as the most prevalent respiratory pathogen that frequently leads to pneumonia and death (Foreyt 1995; Garde and others 2005; Martin and others 1996). *Pasteurella multocida* can also be important in the pneumonia complex. Some of the most recent and yet to be published work indicates that a *Mycoplasma* spp. bacteria may consistently be involved in bighorn sheep respiratory disease deaths (Cassirer, personal communication) in some locations. Black and others (1988) reported that a captive herd of Dall's sheep contracted *Mycoplasma ovipneumonia* infections after contact with domestic sheep. The pathology and epidemiology of *Mycoplasma*-induced pneumonia in sheep are somewhat different from those caused only by highly pathogenic bacteria. A review of *Pasteurella*-related pneumonia can be found in Frank and others (2004). An overview of the many pathogens of concern and the risks associated with them can be found in Garde and others (2005).

All ungulates, except llamas, carry some strains of *Mannheimia haemolytica* (Foreyt 1995). Bighorn sheep appear to be behaviorally attracted to domestic sheep and goats, but not to cattle or llamas. Since *Mannheimia* spp. and *Pasteurella* spp. bacteria transmission requires very close (less than 60 ft) contact or transfer of mucus through coughing or sneezing, it is more likely to occur between bighorn sheep and domestic sheep or goats (Dixon and others 2002) that are behaviorally attracted to one another.

Bighorn sheep appear to be more susceptible to respiratory disease than are domestic sheep. Dubay and others (2002) and Miller (2001) suggested that bighorn sheep did not co-evolve with the same set of pathogens as domestic sheep because of an evolutionary distance between them. Hiendleder and others (2002) estimated this distance at 5.63 million years. In addition, bighorn sheep immune response cells have a reduced capacity to kill bacteria compared to domestic sheep immune function (Dubay and others 2002; Frank and others 2004; Silflow and others 1993). This observation provides a very plausible reason why bighorn sheep may die of bacterial respiratory disease and pneumonia when in contact with domestic sheep while the domestics show no signs of disease.

Bighorn sheep die-offs due to pneumonia have occurred without any known association with domestic sheep (Foreyt 1989; Goodson 1982; Onderka and Wishart 1984; Rudolph and others 2007; Ryder and others 1994). However, when contact between wild sheep and domestic sheep and goats is documented, the severity of the wild sheep die-off is typically more pronounced (Aune and others 1998; Martin and others 1996). George and others (2008) documented that contact with a single domestic ram coincided with a 50 percent die-off in three interconnected herds.

DNA fingerprinting was used to investigate the origin of bacteria leading to death in bighorn sheep (Foreyt and others 1994; Jaworski and others 1993). Bacterial DNA isolated from dead bighorns originated in domestic sheep and had not been present in bighorn sheep before they were exposed. The source of DNA was *Mannheimia haemolytica* (Biotype A, Serotype 2). Research at a variety of facilities (Washington State University, Department of Agriculture, Edmonton, Canada, and Caine Veterinary Center) has shown that specific types of *M. haemolytica* and *Pasturella multocida* can be transmitted between bighorn sheep and domestic sheep (Foreyt 1989, 1990, 1992a; Hunter 1995a; Onderka and Wishart 1988).

In free-ranging conditions, domestic and bighorn sheep association will likely result in bighorn sheep deaths without adversely affecting domestic sheep. Determination by DNA fingerprinting of a shared *Mannheimia haemolytica* between domestic sheep and bighorn sheep indicates that the bacteria was transmitted between these two species under field conditions (Hunter 1995b; Hunter and others in prep).

Demographic Effects

Martin and others (1996) summarized over 30 cases where bighorn die-offs are believed to have resulted from contact with domestic sheep. In many cases, over 50 percent of the bighorn herd died. Domestic sheep always remained healthy.

When respiratory disease occurs in a population of bighorn sheep, mortality normally occurs in all age classes. Research indicated that lambs born in bighorn sheep herds that experienced a pneumonia episode usually died before 3 months of age (Foreyt 1990). Passive colostrum immunity protects lambs early in life, but when immunity wanes at 6 to 8 weeks of age, they die from pneumonia. Further, surviving ewes generally experienced low lamb survival rates for 3 to 5 years after the initial episode (Coggins and Matthews 1992; Foreyt 1990, 1995; Garde and others 2005; George and others 2008; Hunter 1995a; Ward and others 1992). Thus, it appears that ewes surviving pneumonia remain infectious for several years and transfer the bacteria to their lambs. Because low lamb survival rates usually continue for 3 to 5 years, population recovery can be delayed. Further, Hunter and others (in prep) reported that various *Pasteurella* strains can remain resident in bighorn sheep for months or years after contact with domestic sheep. These infected bighorns may become asymptomatic reservoirs of potentially lethal organisms.

Models have predicted that disease originating from domestic sheep and goats is a problem for mountain sheep. Epps and others (2004) noted that the presence of domestic sheep grazing allotments was negatively correlated with mountain sheep population persistence. Proximity of domestic sheep as a factor in the dynamics of mountain sheep populations is a major consideration in the models constructed by Gross and others (1997, 2000). Clifford and others (2007) quantitatively evaluated the degree of risk between domestic and bighorn sheep for Sierra Nevada bighorn sheep (*Ovis canadensis californiana*).

No published reports could be found that document fenced or free-ranging bighorn sheep herds remaining healthy when living directly with domestic sheep herds.

Pertinent Findings

Legal

The disease related conflict between domestic sheep and bighorn sheep was tested in the United States District Court (Oregon) in 1995. The following summarizes United States Magistrate Judge Donald C. Ashmanskas' findings: "Scientific research supports a finding that when bighorn sheep intermingle with domestic sheep, large numbers of bighorn sheep die. While the exact reason for this result may be in question, it is clear that the die-offs occur. An incompatibility exists between the two species, and there is no way to avoid the incompatibility other than to keep the domestics and the bighorns separate" (Ashmanskas 1995).

Payette Science Panel Findings and Recommendations

A science panel was convened in November 2006 to provide additional science-based information regarding disease transmission and the associated risks for the Payette National Forest. Although focused specifically on the Payette risk analysis, the panel's conclusions are applicable to all areas where domestic sheep or goats and bighorn sheep co-exist. The panelists, who were scientists from the livestock and wildlife disease communities, focused on disease and mortality concerns and jointly developed the following statements[1] (USDA Forest Service 2006):

1a) Scientific observation and field studies demonstrate that "contact" between domestic sheep and bighorn sheep is possible under range conditions. This contact increases the risk of subsequent bighorn sheep mortality and reduced recruitment, primarily due to respiratory disease.

1b) The complete range of mechanisms/causal agents that lead to epizootic disease events cannot be conclusively proven at this point.

1c) Given the previous two statements, it is prudent to undertake management to prevent contact between these species.

2) Not all bighorn sheep epizootic disease events can be attributed to contact with domestic sheep.

3) Gregarious behavior of bighorn sheep and domestic sheep may exacerbate the potential for disease introductions and transmission.

4) Dispersal, migratory, and exploratory behaviors of individual bighorn sheep traveling between populations may exacerbate the potential for disease introduction and transmission.

5) There are factors (for example, translocation, habitat improvement, harvest, weather, nutrition, fire, interspecies competition, and predation), some that can be managed and some that cannot, that can influence bighorn sheep population viability.

6) *Pasteurellaceae* and other bacteria, viruses, and other agents may occur in healthy, free-ranging bighorn sheep.

[1] References to domestic sheep also apply to domestic goats.

Western Association of Fish and Wildlife Agency Findings

In January 2007, the Western Association of Fish and Wildlife Agencies (WAFWA), a group of 23 state and provincial wildlife agencies from the western United States and western Canada, established a Wild Sheep Working Group (WSWG). Comprised of bighorn sheep managers and veterinarians, WSWG was requested to provide a comprehensive, west-wide assessment of all facets of wild sheep management. The following conclusions from their June 21, 2007 final report, which WAFWA unanimously endorsed in July 2007, are relevant to this disease overview:

1) Over the past 30 years, there has been a steadily increasing body of anecdotal and empirical evidence underscoring the potential risk of disease transmission from domestic sheep and goats to wild sheep.
2) There is a preponderance of evidence, taken collectively from a wide variety of observations, that indicates significant risk of disease transmission from domestic sheep and goats to wild sheep exists.
3) Effective separation (both temporal and/or spatial) between wild sheep and domestic sheep and goats should be a primary management goal of state and provincial agencies responsible for wildlife management.
4) We concur with statements developed and adopted by the interdisciplinary Payette National Forest Science Panel (listed above).
5) We recognize that it is impossible to achieve zero risk of contact or disease transmission: however, we also recognize there are many ways to work proactively toward minimizing or eliminating interaction between these species.
6) We developed management guidelines for use by all agencies, organizations, domestic producers, and private land owners.

Conclusions

The scientific literature and expert panels support the conclusion that bighorn and domestic sheep/goats should not occupy the same ranges simultaneously or be managed in close proximity to each other if maintenance of a bighorn sheep population is a management objective. The literature is clear regarding the high probability of bighorn sheep dying of pneumonia following contact with domestic sheep. Efforts to identify organisms causing pneumonia in bighorn sheep following contact with domestic sheep have identified many potentially pathogenic bacteria of multiple species, but the specific mechanisms/causal agents that lead to epizootic disease events are not completely understood.

Managment Implications

Pressing resource management decisions cannot wait for a complete understanding of all aspects of respiratory disease processes in bighorn sheep. In landscapes where management objectives include the maintenance or enhancement of bighorn sheep populations, the risk of potential of disease transmission between domestic sheep/goats and bighorn sheep must be addressed. The available information supports creating spatial and/or temporal separation between domestic sheep/goats and bighorn sheep as a prudent management technique to manage the risk of disease transmission.

(Callan and others 1991; Coggins 1988, 2002; Coggins and Matthews 1992; Desert Bighorn Council 1990; Festa-Bianchet 1988; Foreyt 1989, 1990, 1992a, 1992b, 1994, 1995; Foreyt and Jessup 1982; Foreyt and others 1994; Garde and others 2005; Goodson 1982; Hunt 1980; Hunter 1995a; Hunter and others in prep; Jessup 1980, 1982, 1985; Kistner 1982; Martin and others 1996; Onderka 1986; Onderka and Wishart 1988; Pybus and others 1994; Ward and others 1997; Wishart 1983). Recent disease incidents involving domestic goats have resulted in the same conclusion (Garde and others 2005; Heffelfinger 2004; Jansen and others 2006).

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A Process for Identifying and Managing Risk of Contact between Sierra Nevada Bighorn Sheep and Domestic Sheep

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INTRODUCTION

During a Sierra Nevada Bighorn Sheep Recovery Team (Team) meeting, made up of science and stakeholder teams, held on April 26-27, 2006, a decision was made that the disease risk assessment portion of Appendix B (Sierra Nevada Bighorn Sheep Recovery and Domestic Livestock: Preliminary Risk Assessment of Disease in the Eastern Sierra) provided in the Draft Final Recovery Plan for the Sierra Nevada Bighorn Sheep (*Ovis canadensis californiana*) (U. S. Fish and Wildlife Service 2006) should be redeveloped. To avoid delay in the completion of the final recovery plan for the Sierra Nevada Bighorn Sheep, the Team decided that this portion of Appendix B would be removed from the final plan, and a new disease risk assessment would be developed. This document provides a means to better understand and assess the likelihood of contact between domestic sheep (and goats) and Sierra Nevada bighorn sheep, a federally endangered species. The likelihood of contact plays a role in the risk of transmitting diseases to Sierra Nevada bighorn sheep from domestic sheep in the Sierra Nevada (Tuolumne, Mono, Fresno, Inyo, and Tulare Counties) California. Contact may result in the possible introduction of new pathogens to Sierra Nevada bighorn sheep that may cause pneumonia. There is concern that this could lead to the loss of entire bighorn sheep herds in the Sierra Nevada.

The Team assigned a subgroup representing the Team to revisit the risk assessment and develop a technique for assessing the risk of disease transmission between domestic sheep (and goats) and Sierra Nevada bighorn sheep. Subgroup representatives included land management agencies (Forest Service), wildlife management agencies (California Department of Fish and Game, U. S. Fish and Wildlife Service), sheep producers (F.I.M. Corp., Echenique Livestock), environmental organizations, and the Science Team.

Amongst the subgroup, there are varying opinions on the adequacy of the best available science related to disease transmission from domestic sheep to bighorn sheep in the wild. We did agree that disease transmission may be possible in the wild, and therefore, the goal is to prevent contact between domestic sheep (and goats) and Sierra Nevada bighorn sheep.

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In this document we describe an approach for assessing the risk of contact between Sierra Nevada bighorn sheep and domestic sheep (and goats) and discuss specific grazing practices we consider practicable to manage that risk. This approach assesses the risk by overlaying domestic sheep use areas with predicted Sierra Nevada bighorn sheep locations derived from a model based on habitat preferences and least-cost pathway analysis. This approach will assist in determining areas Sierra Nevada bighorn sheep are likely to travel/occupy in relation to movement of domestic sheep through grazing allotments. This process will be updated as needed or as new information becomes available as resources allow.

We address the factor/concerns related to disease transmission between domestic sheep (and goats) and Sierra Nevada bighorn sheep in four sections: I. Ecology of Sierra Nevada Bighorn Sheep, II. Spatial Assessment of Risk of Contact between Sierra Nevada Bighorn Sheep and Domestic Sheep (and Goats), III. Grazing Practices for Reducing and Detecting Straying of Domestic Sheep, and IV. Risk Assessment Implementation. The purpose of this approach is to provide land, wildlife, and livestock managers a tool for determining risk of contact between livestock and Sierra Nevada bighorn sheep and identifying ways to prevent contact.

The biology and historic distribution of bighorn sheep and the history of domestic sheep grazing in the Sierra Nevada are discussed in the Recovery Plan for the Sierra Nevada Bighorn Sheep (U. S. Fish and Wildlife Service 2007). Readers of this document should review the final recovery plan's Appendix B and other scientific literature which discusses diseases and concerns related to domestic livestock and bighorn sheep management.

While we developed this document for management of domestic sheep (and goats) near Sierra Nevada bighorn sheep, application of this assessment may assist others in recognizing potential conflicts and using specified grazing practices to reduce the likelihood of contact between domestic sheep (and goats) and bighorn sheep in their areas of concern. Likely users of this document include land managers, wildlife managers, and sheep and goat producers to assist in responsibly managing livestock in proximity to bighorn sheep. This document could also be provided to the general public that raises backyard sheep and goats, including 4H members and other interested parties, to increase awareness and thus assist in reducing the likelihood of contact between bighorn sheep and domestic sheep and goats.

SECTION I - ECOLOGY OF SIERRA NEVADA BIGHORN SHEEP

This section provides a brief overview of the ecology of Sierra Nevada bighorn sheep. For a full discussion, refer to the final recovery plan (U. S. Fish and Wildlife Service 2007). Sierra Nevada bighorn sheep are a mountain dwelling ungulate whose life history is associated with the acquisition of food and mates in a rugged, topographically diverse landscape. In their search for optimal foraging habitat, Sierra Nevada bighorn sheep climb to elevations as high as 4,267 meters (14,000 feet) during the summer following green forage as it progresses up the mountains with increasing temperatures. They tend to remain at high elevations through the autumn breeding season (the rut) if weather permits, but rams exhibit a greater tendency to use a range of elevations throughout the year. Bighorn sheep have a polygynous mating system with males competing for breeding dominance during a rutting period that extends from late September through December. The peak of mating occurs in early November with a 180 day gestation period following conception. As winter snows arrive, most bighorn ewes are pregnant and the rams are in poor condition. In the winter, they seek areas with forage that is not buried by snow. Such areas may be low elevation [1,372 – 2,438 meters (4,500 – 8,000 feet)] ranges or high elevation [above 3,353 meters (11,000 feet)], wind scoured, alpine ridgelines. If they migrate to low elevation ranges, they typically remain there into April and have access to early green-up that results from warmer temperatures associated with lower elevations. Most lambs are born during May but may be born between mid April and early July. As new forages grow in the spring with warming temperatures, bighorn sheep begin migrating to higher elevations and ewes give birth to lambs in extremely steep terrain. Within a matter of days, newborn lambs begin following their mothers and continue migrating to higher elevations. Summer movements allow for maximizing intake of nutritious forage while ensuring access to steep, escape terrain, especially for ewes with lambs.

Bighorn sheep in the Sierra Nevada are elevational migrants with annual home ranges of ewes and rams averaging 53 square kilometers (20.5 square miles) and 100 square kilometers (38.6 square miles), respectively. Long distance movements may be associated with seasonal migration or forays by rams in search of mates. Movements of a Sierra Nevada bighorn sheep ram of more than 50 kilometers (31 miles) (measured in straight line travel distances) has been measured during the rut. Movements beyond core home ranges may occur in less suitable habitat. Winter ranges are characterized by snow-free, wind-scoured, or south-facing slopes that support abundant shrub and herbaceous forage. In contrast, summer ranges tend to be high elevation slopes in proximity to lush, alpine meadows. Forage quantity and quality on ranges is determined by precipitation, plant composition, and competition among conspecifics, with bighorn sheep population limitation occurring at higher densities through the mechanisms of density dependence.

SECTION II - SPATIAL ASSESSMENT OF RISK OF CONTACT BETWEEN SIERRA NEVADA BIGHORN SHEEP AND DOMESTIC SHEEP (AND GOATS)

We have developed an objective technique for determining the relative likelihood that Sierra Nevada bighorn sheep will move into or otherwise use habitat allotted to or otherwise grazed by domestic sheep (and goats). The possibility of contact between Sierra Nevada bighorn sheep and domestic sheep (and goats) can be determined, in part, by quantitatively estimating the relative likelihood of a bighorn sheep moving into a domestic sheep allotment. This approach uses a Geographic Information System (GIS) to approximate the likelihood of a bighorn sheep moving into or through habitat by incorporating known locations of bighorn sheep, habitat characteristics, and domestic sheep allotments. The techniques used are well established in the literature and include habitat suitability modeling (*e.g.*, Zeigenfuss et al. 2000) and least-cost pathway modeling (*e.g.*, Beazley et al. 2005).

The methods are summarized briefly here and then described in more detail below:

1. Construct a bighorn sheep *habitat suitability model* and input it into ArcGIS.
2. Convert the habitat model suitability to a *resistance surface (i.e.,* layer*)*.
3. Identify *source points* for bighorn sheep movements.
4. Determine the *cost of movements* through the landscape for bighorn sheep from source point locations by creating a model of inverse weighted distances. This is referred to as the inverted *cost surface*.
5. Overlay the *outcomes* of bighorn sheep predictive modeling with domestic sheep allotment boundaries.
6. Calculate a *risk value* as the product of the spatial and temporal aspects of grazing allotments.

1. Construct Bighorn Sheep Habitat Suitability Model

A habitat suitability model for bighorn sheep was created using locations of bighorn sheep obtained from Global Positioning System (GPS) collars (Johnson et al. 2005). Bighorn sheep use and non-use of particular landscape features were identified using a multivariate logistic regression to predict preference of habitat by bighorn sheep. Landscape features considered include vegetation type (forested or non-forested), slope, aspect, hillshade, elevation, ruggedness, and distance to escape terrain (Johnson et al. 2005). The habitat suitability model was then computed in ArcGIS using a resource selection function wherein each pixel on the landscape was assigned a value that represents its suitability (*i.e.*, probability of bighorn preference) as bighorn habitat. This model forms the habitat suitability surface.

2. Create Resistance Surface

In order to determine the relative likelihood that a bighorn will pass through a particular portion of the landscape, the *habitat suitability surface* was inverted to create a *resistance surface*. In this layer, each pixel represents its *lack* of suitability and hence the "cost" associated with moving through the habitat at that location. "Cost" is defined by distance and landscape features that are perceived as less desirable (*e.g.*, not adjacent to rugged escape terrain) for travel by bighorn sheep. The costs of movement can be defined in terms of lack of available forage, proximity to escape terrain, etc.

3. Identify Source Points for Bighorn Sheep Movement

The relative likelihood of contact between bighorn sheep and domestic sheep (and goats) can be defined not only by the suitability of habitat for bighorn sheep in or adjacent to allotments but also by the actual or potential presence of bighorn sheep. Therefore, we next identified "source", or potential starting points for modeling bighorn sheep movement paths occurring within the core range (the area most consistently used during daily activities) of each radio-collared individual bighorn using GPS, ground, and aerial telemetry locations. Then, locations occurring within the 50 percent core home range were determined and used as the "source points" for identifying potential movement paths for individual bighorn sheep.

4. Determine Cost of Movements for Bighorn Sheep on the Landscape from Source Points (Bighorn Sheep Surface)

Using the source point of each individual bighorn sheep as a starting location, the "cost" associated with bighorn sheep moving out from that point will be calculated in ArcGIS. This approach utilizes the minimum cost distance associated with any individual bighorn sheep location to create a single surface. This composite layer represents the cumulative cost associated with travel to that point on the landscape by any individual. The cost is a function of the straight-line distance of a pixel from a source point and the habitat suitability value associated with that particular pixel and all pixels in the intervening space along the least-cost path. The cost surface is bounded by a maximum distance representing the maximum dispersal distance that a bighorn sheep is likely to travel in the region. The final cost surface is inverted such that values further from the source points represent lower risk (0), while those adjacent to source points represent higher risk (1) (inverted cost surface).

5. Overlay Inverted Cost Surface onto Domestic Sheep Allotment Map

The next step assigns each domestic sheep allotment a value that describes the relative likelihood of a bighorn sheep traveling adjacent to or into that allotment. This is accomplished by overlaying the inverted cost surface with the allotment surface.

6. Calculate Risk Value

The risk of contact is related to the amount of time and the temporal proximity to the fall bighorn sheep rut (as measured from January 1st) that domestic sheep are in allotments. The risk value for each allotment (or section of an allotment) was calculated as the product of the spatial and temporal aspects of grazing. The spatial component is the mean inverse weighted distance (MIWD; inverted cost surface). The temporal component is the sum of the number of days that the allotment is grazed and the latest Julian date that the allotment is grazed. Our use of the Julian date is based on the assumption that Sierra Nevada bighorn sheep are more likely to travel long distances as the rutting dates (September-December) approach.

$$\text{Risk} = \text{MIWD} \times (\text{number of grazing days} + \text{Julian Date})$$

* MIWD is the mean relative likelihood that a bighorn sheep will occupy a given allotment. Julian Date is a serial number equal to the number of days elapsed since January 1 of a year. For example, February 15 is equal to Julian Date 46.

The model described here represents an effort to utilize the most current and detailed information available at the time the model was developed. Nevertheless, the model does have limitations. While the initial goal in developing the model was to predict the probability of contact between bighorn sheep and domestic sheep, the lack of quantitative data on direct contact *(i.e.*, no bighorn sheep wearing GPS collars in this recovery area has made direct contact with domestic sheep) precluded such a level of specificity. Thus the risk values that are output by the model represent a relative likelihood of contact rather than an absolute one. GPS collars have been deployed on 25 - 75 percent of the rams in the Northern and Central Recovery Units. While this represents a high level of monitoring, not all movements have been documented and hence the source points used represent a minimum. Of the GIS layers incorporated into the habitat suitability layer, the vegetation layer used to identify forested-nonforested vegetation was limited in resolution during development. Consequently, the model may be less sensitive in predicting use or avoidance of areas based on vegetation cover. Vegetation GIS layers continue to improve in resolution on an annual basis, it is expected that future versions of the model will more accurately reflect bighorn use based on preferences for types of vegetation. The model focuses on predicting the potential for contact through movement by bighorn sheep into allotments, however, contact may also occur through straying of domestic sheep. Although not specifically addressed, the risks associated with straying may be approximated by assessing the proximity of allotments to occupied bighorn habitat.

SECTION III – GRAZING PRACTICES FOR REDUCING AND DETECTING STRAYING OF DOMESTIC SHEEP

The prevention of straying of domestic sheep and goats is a high priority in the Sierra Nevada because unmanaged sheep or goats could mingle with Sierra Nevada bighorn sheep, particularly when grazing at high elevations. This section references grazing practices for domestic sheep that should reduce the straying of domestic sheep (and goats) and thereby reduce the likelihood of contact with Sierra Nevada bighorn sheep (Lynch et al. 1992).

The analysis in Clifford et al. (2007) showed a significant reduction in the probability of Sierra Nevada bighorn sheep respiratory disease transmission by not grazing domestic sheep during the rut, limiting grazing days by domestic sheep (76 to 81 percent reduction for 2005 and 2006 schedules compared with entire grazing season) and vigilant domestic sheep grazing management (48 to 62 percent reduction with no 1-kilometer spatial buffer). The utilization of the 2006 grazing strategy, allotment boundary adjustment, and vigilant management to prevent strays reduced the annual probability of respiratory disease transmission from 7 percent to 1.2 percent per year in the Northern Recovery Unit. This supports the development of possible mitigation strategies.

There are factors which may cause individuals or small groups of domestic sheep (or goats) to stray from their band. The following is a partial list (as additional factors may become realized at a later date) of possible/likely reasons domestic sheep stray which results in an increase in risk of contact between domestic and bighorn sheep. These factors include: 1) Sick or lame sheep; 2) Lambs separated from ewes or ewes separated from the band; 3) Inattentive or absent sheepherders; 4) Predator attacks or attempts on sheep; 5) Use of either non-gregarious sheep breeds or goats as leaders; 6) Disturbance of sheep by recreationists, especially hikers with dogs, motorized off-road vehicles, etc.; 7) Herd management activities aside from grazing, including: off-loading of trucks; weaning and shipping lambs; trailing, especially with small lambs; driving (herding) to corrals or other unusual location for counting; or for other activities that disturb domestic sheep; 8) Inadequate preferred forage and/or livestock water; 9) Sheepherder's camp location; 10) Sheep bedding ground location; 11) Grazing through taller vegetation (e.g., forests, tall sagebrush, mountain mahogany); 12) Environmental events including thunder, lightening, high winds, and unseasonal snowstorms, wildfire, moonlit nights; 13) Inattentive or absent guard or herding dogs; 14) Domestic sheep band size too large (*i.e.*, greater than 900 to 2,400 individuals, see item C below); 15) Non gregarious domestic sheep breed; and 16) Poorly confined backyard sheep and goats.

The grazing practices listed below are considered to be measures that exemplify intensively managed domestic sheep grazing operations. When applied in their entirety, they should reduce the risk of straying and assist in reducing the likelihood of contact between domestic sheep (and goats) and Sierra Nevada bighorn sheep. Some practices mitigate more than one factor that may cause straying. Others provide a method for detecting that an individual(s) has strayed from the band. We have grouped these grazing practices into two categories: verifiable and unverifiable. These categories were identified because certain practices are more readily monitored on the ground by agency personnel than others. In addition, though not included in our list of measures to be implemented in their entirety, we mention that the construction and maintenance of electric or boundary fences can be useful in some situations to contain domestic sheep (*e.g.*, around bedding grounds as a temporary measure on public lands; around domestic backyard flocks).

Grazing Practices to Reduce and Detect Straying of Domestic Sheep and Goats

Verifiable Grazing Practices

A. Select only highly gregarious breeds of sheep (*i.e.*, Merino, Rambouillet, "Western white-faced ewes", fine wools and crosses thereof) (American Sheep Industry Association, Inc. 2003). Exceptions are during those brief periods of time when rams of non-gregarious breeds (*e.g.*, Suffolk) are present; ewes of gregarious breeds will continue to stay together as a band and will also cause the non-gregarious rams to stay with the band through the breeding season only.

B. The onset of estrus in domestic sheep is influenced by breed, season (fall) and cessation of lactation. Use ewes that are pregnant (determined by ultrasound preferably) or nursing lambs (twins preferably). These are the most suitable groups to graze nearest to bighorn sheep habitat while open ewes, yearling replacement ewes, and ewes that have lost their lambs are the least suitable.

C. Maintain a band size of less than 1,500 dry ewes or yearlings, 900 ewes with single lambs (1,800 total), or 700-800 ewes with twin lambs (2,100 to 2,400 total). These numbers are less than historically established domestic sheep numbers handled by a herder and dogs.

D. Require instruction/training and supervision to ranch and agency staff members (*i.e.*, camptenders and sheepherders) specific to Sierra Nevada bighorn sheep identification, prevention of contact, and escape procedures. Ranch owners and camptenders provide frequent instructions to the sheepherders concerning locations where there is forage and water available for domestic sheep and monitor that the grazing standards and guidelines are being followed. Document meetings and instructions to sheepherders in the log book (two examples of log book sheets are provided in Attachments 1 and 2; examples of instructional materials are provided in Attachment 3).

E. Remove sick or physically disabled sheep from the band; provide prompt veterinary treatment to injured sheep that are not disabled according to written protocols that should be established by the operator (a protocol example is provided in Attachment 4).

F. Place mature and effective guard dogs and herding dogs with the bands (recommended at least two herding and two guard dogs per band). Female dogs in heat should not be placed on allotments. Please refer to the American Sheep Industry Association, Inc. (2003) publication.

G. Conduct full counts of all individuals (ewes, rams, and lambs) when moving onto and off of each allotment to establish a baseline. Land managers should be present during these counts.

H. Maintain and record a ratio of at least 1 marker sheep to every 20 adult sheep. This ratio needs to be kept during the entire grazing season by replacing marker sheep as needed.

I. Count marker sheep on regular basis (at least twice per day). In the event that domestic sheep scatter, complete a full count as soon as possible.

J. Place bells on a customary number (at least a ratio of 1:100) of mature ewes to serve as warning sound for herder and to serve as identification and location of sheep to other sheep. If using "bell" sheep as markers, place an identifying mark on the bell sheep in case the bell is lost.

K. Require that each sheepherder consistently use a log book or other record keeping aid (Attachments 1 and 2). If grazing federal lands, the log book will be made available to appropriate federal employees upon request; if there is an issue with the log book, land managers will contact the permittee.

L. Select herder's camp, nighttime bedding ground, and midday (siesta) bedding ground locations that maintain communication between guard dogs and herding dogs by smell, sound (barking), and sight, and to take advantage of both guard dog and herding dog reticular activating systems. If grazing federal lands, one must adhere to established "bed ground" standards.

M. Select camp locations and bedding ground locations that will be acceptable to the sheep and thus result in the sheep remaining within the bedding grounds. If grazing federal lands, one must adhere to established "bed ground" standards.

N. Do not trail further than 5 miles in a day or stop trailing when sheep or lambs show signs of fatigue, whichever comes first; consider trucking instead of trailing. Please be aware that the domestic sheep may cross multi-jurisdictional lands during trailing.

O. Truck in water if needed (thirsty sheep are more likely to stray).

P. Develop and follow a plan for locating and reacquiring stray sheep. This plan, developed in conjunction with the land management agency, can be considered an Escape Management/Communication Protocol Plan. It indicates that if at any time during the grazing season, a domestic sheep is determined missing from the band on the allotments, the permittee will immediately initiate a comprehensive search and notify the land manager as defined in the plan. The search would continue until the stray is located and its locations evaluated in relation to Sierra Nevada bighorn sheep locations. The results will be immediately reported to the designated official. An example plan is available from the Humboldt-Toiyabe National Forest, Bridgeport Ranger District, Bridgeport, California.

Q. Require that sheepherder use communication equipment such as cell phones so that they may contact appropriate personnel in case of straying or Sierra Nevada bighorn sheep sightings.

R. Require that sheepherder use GPS receiver and record GPS locations in the sheepherder's log book.

Unverifiable Grazing Practices

S. Place the more experienced, informed, and responsible sheepherders with bands of sheep on allotments located nearer to Sierra Nevada bighorn sheep habitat.

T. Avoid moving domestic sheep through dense vegetation (go around instead of through) where possible.

U. Increase sheepherder vigilance on bright moonlit nights.

SECTION IV – RISK ASSESSMENT IMPLEMENTATION

The following describes the steps to be used by land management and regulatory agencies to: (1) assess the relative likelihood of contact between Sierra Nevada bighorn sheep and domestic sheep (and goats) on allotments, and (2) determine how to prevent such contact from occurring. As recovery goals are met (U. S. Fish and Wildlife Service 2007), the number and distribution of Sierra Nevada bighorn sheep will increase. Therefore, the likelihood of contact between bighorn sheep and domestic sheep will also increase. The assessment will need to be updated as new information becomes available. It is assumed that coordination among agencies and permittees is occurring during this process. Land management agencies should evaluate the need for section 7 consultation under the Endangered Species Act of 1973, as amended, and initiate consultation with the U. S. Fish and Wildlife Service as appropriate.

We envision a five step process that can be used by wildlife and land managers as follows:

Step 1. Determine the relative likelihood that a Sierra Nevada bighorn sheep will utilize habitat where domestic sheep are grazed.

Use the spatial risk model described above to quantitatively measure the relative likelihood that a Sierra Nevada bighorn sheep will utilize habitat where domestic sheep are grazed. Attachment 6 provides a model run output completed in 2008.

The model will be updated by the California Department of Fish and Game in coordination with land management agencies, as new information is collected on bighorn sheep movement and domestic sheep allotment management. Prior to a model update, land management agencies will provide the California Department of Fish and Game of any major management modifications (*i.e.*, boundary line changes, permitted and actual use, allotment status, etc.). California Department of Fish and Game will share model output (including intermediate analyses upon request) with land management and regulatory agencies to inform their determinations regarding grazing domestic sheep allotments. Land management agencies should share these outputs with permittees. Model updates will be contingent on funding by state and federal agencies or other sources.

We stress that current and comprehensive data is essential if the model is expected to provide managers with accurate information that reflect current conditions. The model should be rerun when new information (*e.g.*, changes in bighorn sheep distribution/movement, habitat conditions and/or domestic sheep grazing regimes) is available. Model inputs should be clearly defined with each update (*e.g.*, Attachment 6).

Step 2. Assess whether grazing domestic sheep in a specific allotment could result in contact with bighorn sheep.

The land management agency, in coordination with the U. S. Fish and Wildlife Service, the California Department of Fish and Game, and the permittee if necessary, should review the output of the spatial model and make a determination as to whether grazing domestic sheep in a specific allotment could result in contact with bighorn sheep. It should be recognized that while the model was based on the best available data, any modeling effort inherently does not predict every aspect of reality. Also the broad habitat preferences exhibited by Sierra Nevada bighorn sheep rams result in reduced specificity of the model's predictions. In addition to the model output, other documents and information needs to be considered during this coordination process. These documents include forest plans, resource management plans, the final recovery plan, peer reviewed literature, and any other applicable laws and regulations. Information on the specific allotments in question, such as, Sierra Nevada bighorn sheep habitat, vegetation types, spatial features (*i.e.*, rock outcrops, ridges), grazing rotations, grazing patterns, other land uses (*i.e.*, recreation, residences, resorts), and Sierra Nevada bighorn sheep locations should also be considered. Managers should also consider the risks associated with straying by domestic sheep outside of the rut period in allotments that are in close proximity to bighorn sheep habitat. In making their evaluations, managers should consider the cumulative impact posed by allotments in the context of both space (*i.e.*, more than one allotment) and time (*i.e.*, more than one year). For example, managers with multiple allotments or those adjacent to an allotment managed by a different entity should not consider each allotment in isolation. As the recovery plan states, "the potential for contact between bighorn sheep and domestic sheep or goats must be eliminated to avoid the possibility of a catastrophic epizootic" (U. S. Fish and Wildlife Service 2007).

If a determination is made that grazing domestic sheep on a specific allotment could result in contact with bighorn sheep then land managers should proceed to step 3. If contact is not predicted, modification of grazing practices to prevent disease transmission is not essential.

Step 3. Determine whether changes in the temporal (*e.g.*, seasonal closures) or spatial use of allotments would prevent contact between bighorn sheep and domestic sheep or goats.

Managers, in coordination, should determine if making changes in the temporal (*e.g.*, seasonal closures) or spatial use of specific allotments would prevent contact between bighorn sheep and domestic sheep. If it is determined that changes in the temporal or spatial use of specific allotments would *not* prevent contact between bighorn sheep and domestic sheep then land managers should proceed to step 4.

Step 4. Determine whether implementing the grazing practices detailed in Section III above would prevent contact between bighorn and domestic sheep.

Managers should determine whether implementing the grazing practices, described in Section III in their entirety, would prevent contact between bighorn sheep and domestic sheep. We believe that some likelihood of contact may be mitigated through the use of grazing practices. However, because the likelihood of contact is higher when domestic sheep are grazed in proximity to habitat occupied by bighorn sheep the only method that ensures that contact can not occur is avoiding the use of overlapping ranges by the two species. Therefore, the use of grazing practices can not be expected to prevent contact in every situation.

If it is determined that implementation of the grazing practices would prevent contact between domestic sheep and bighorn sheep and grazing is subsequently permitted, then managers should proceed to Step 5. If it is determined that contact between bighorn sheep and domestic sheep (or goats) cannot be prevented on an allotment(s), we recommend closure to domestic sheep (and goats) (see Section E of the final recovery plan).

Step 5. Monitor and verify whether grazing practices are being implemented and assess their effectiveness in reducing straying of domestic sheep.

It is the permittee's responsibility to adhere to any standard and guidelines that are a part of their term grazing permit. The responsibility for monitoring and verifying that livestock producers are using the prescribed grazing practices during the grazing season is the responsibility of the land management agencies (Attachment 5).

For allotments where grazing is permitted in Step 4 based on implementation of grazing practices, managers should, on an annual basis, compile monitoring and reporting information from permittees and monitoring and verification reporting from agency personnel. This information should be used to verify that grazing practices are being implemented as prescribed and to assess whether the mitigation measures are effectively preventing straying of domestic sheep (and goats). We consider this an essential component of implementation that will allow the U. S. Fish and Wildlife Service, California Department of Fish and Game, and appropriate land management agencies to assess whether this process is providing needed conservation benefit and will assist in identifying needed changes to it in the future. It will also help to ensure that effective measures are continued and that ineffective measures, which may add cost but no benefit, are discontinued.

FOR MORE INFORMATION:

To obtain information on the risk of contact between domestic sheep (and goats) and Sierra Nevada bighorn sheep on a particular Forest Service or Bureau of Land Management allotment, one should contact the appropriate office located in Bishop or Bridgeport, California. To obtain information on the risk of contact for non allotment areas or private land, one should contact the appropriate office of California Department of Fish and Game in Bishop, California, or the U. S. Fish and Wildlife Service in Ventura, California, or Reno, Nevada.

ACKNOWLEDGEMENTS

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Attachment 1

Log Book

Total Count ______________

Permitte ______________ Allotment ______________ Grazing Season ______________

Date Fecha	Time of Count Hora de Contar	# of Marker Sheep # de Marcas de Borregas	Total Loss Ewe, Ram, Lamb Muertas Borrega, Toro, Borreguito	Cause of Loss Muertas Porque?	Time of GPS Tiempo de GPS	Elevation Location Elevacion Situacion	Notes Nota

Scatter event O weather * predator place either symbol next to count row above as appropriate

Attachment 2

Log Book

FECHA:______________ (Date)

AREA:______________________________ (Allotment or Area)

PAGINA:_________ (Page)

Toros (rams)				Campanas (bells)				Negras (blacks)				Prietas (black-faced)			
ID Nu. (ID No.)	Tiempo (Time):	Tiempo (Time):	Tiempo (Time):	ID Nu. (ID No.)	Tiempo (Time):	Tiempo (Time):	Tiempo (Time):	ID Nu. (ID No.)	Tiempo (Time):	Tiempo (Time):	Tiempo (Time):	ID Nu. (ID No.)	Tiempo (Time):	Tiempo (Time):	Tiempo (Time):

NOTA (notes) –

Aqui tienes que notar el total de animales perdidos. Es necesario indicar el tipo de animal perdido (carnero, oveja, cordero), y la causa de la perdida (enfermidad, animal cojo, despredador). Recomendamos que el visitante firma o inicie el registro, especialmente si hay cambios en el grupo de ovejas. Si posiciones del GPS son indicadores por el grupo de ovejas, pueden ser incluidos aqui.

This section should account for total losses (reduction in band number), and should indicate the type of loss (ram, ewe, lamb), and the reason for the loss (sick, lame, predator). We recommend any visitor initial or sign the log sheet, especially if changes are made to the band for any reason. If GPS locations are indicated for the band, they can be included in this section:

Indicar perdida total (total losses):____________________________

Perdida tipo (type of loss):____________________________

Causa perdido (reason for the loss):____________________________

Visita (visitor):____________________________

GPS sitio (GPS locations):____________________________

Attachment 3

Sierra Nevada Bighorn Sheep Identification Information

Bighorn sheep have a generally stocky build. As adults, Sierra Nevada bighorn sheep stand about three feet tall at the withers (the highest part of the back at the base of the neck of a horse, sheep, etc.) and weigh up to 140 pounds for females and 220 pounds for males. Coat color is variable from almost white to dark brown with a distinctive large white rump patch and a short dark tail. Females carry small narrow horns which rarely exceed 12 inches in length. Mature males carry more massive horns that are notably wide and flaring but relatively narrow at the base for bighorn. Young males (age 1-2) possess horns with shorter lengths than mature males but with broader bases than females. Lamb horns vary in length from 0 to 6 inches.

Carneros salvajes típicamente tienen el un aspecto general bien fuerte. Como adultos, los carneros salvajes del Sierra Nevada miden como 3 pies de altura a los hombros. Las ovejas pesan hasta 140 libras y los carneros hasta 220 libras. El color del pelaje es variable, se encuentran pelajes casi blancos hasta marrón oscuro. Se ve una marca blanca distinta al trasero del animal con una cola corta y oscura. Las ovejas llevan los cuernos estrechos y pequeños que raramente exceden 12 pulgadas en longitud, mientras que los carneros llevan cuernos mas masivos que son notablemente anchos y que son mas separados hacia los puntos. Carneros jóvenes (edades 1-2) tienen cuernos mas pequeños que carneros maduros pero mas anchos que ovejas. Cuernos de los corderos son variable en longitud y miden de 0 a 6 pulgadas.

Contact information:
(informacion de contacto)

California Department of Fish and Game
407 West Line Street, Room 8
Bishop, CA 93514
Telephone: 760-872-1171

Sierra Nevada Bighorn Sheep Pictures

Male Sierra Nevada Bighorn Sheep (SNBS)

Male and female SNBS

Male SNBS

Yearling male and female SNBS

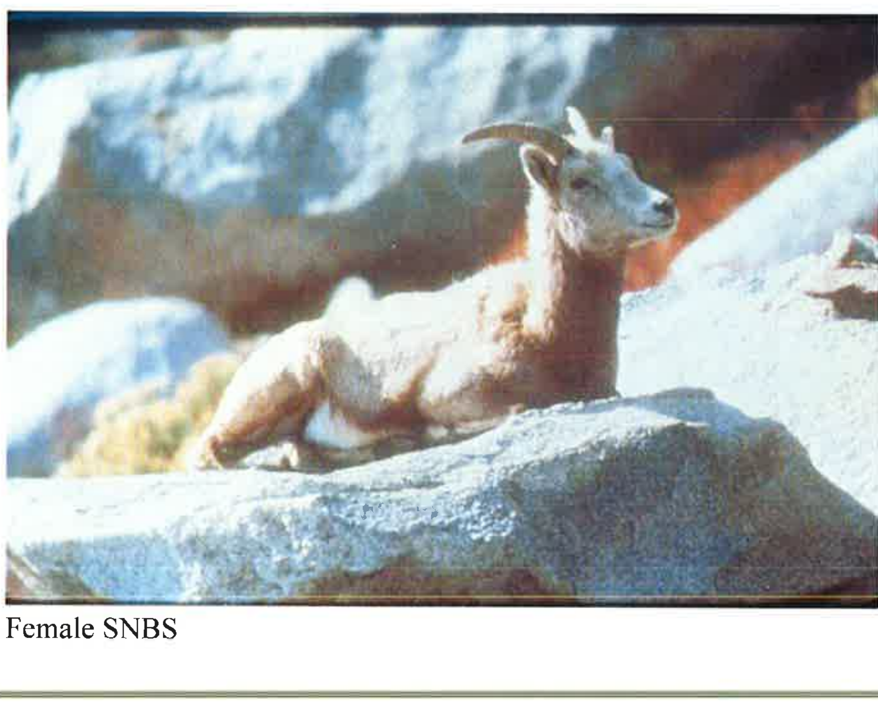
Male and female SNBS

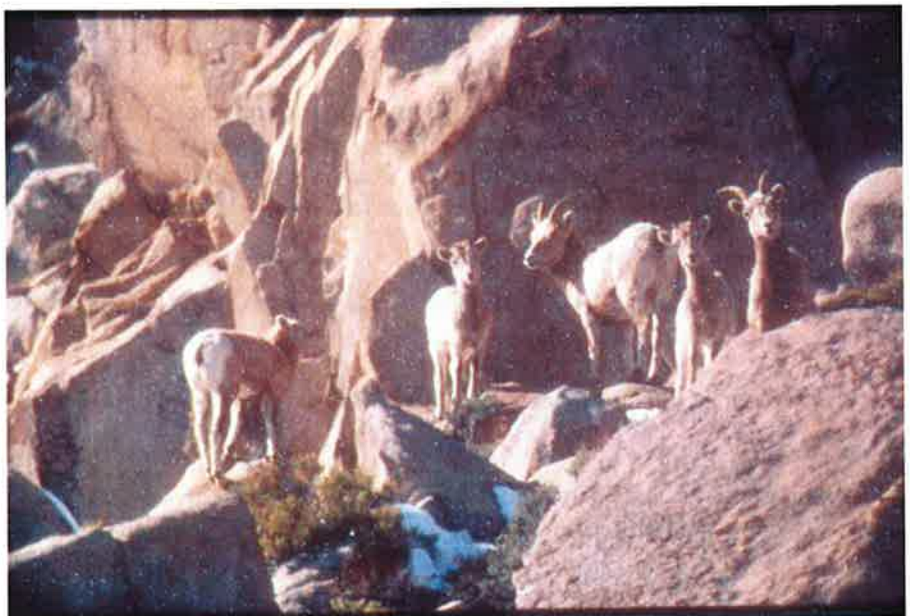
SNBS lamb

Adult female, yearling female, and yearling male

Group of male and female SNBS


SNBS on a ridge top


Female SNBS



Females and juveniles

Male SNBS

Attachment 4

Veterinary Protocol

1. Pre-turnout treatment for internal and external parasites. Products chosen for internal parasites should be effective against stomach worms, lung worms and nose bots. External parasite (post-shearing) treatment must be effective against crawling as well as sucking lice. Usually a pour-on insecticide is needed to treat crawling lice while injectable ivermectins and their derivatives, used for stomach worms, will eliminate sucking lice.

2. No modified live vaccines, i.e. Bluetongue or IBR-BVD-PI3 should be given to sheep within 30 days of turnout.

3. Basic supplies: self stick bandage wrap, duct tape, bandage scissors, 3cc and 12cc syringes, 18G 1-inch needles, and foot trimmers.

4. Drugs and solutions: Hydrogen Peroxide, auto starter fluid with ether, Koportox®, wound insect repellent spray, long acting tetracycline, Penicillin, Baytril®, oxytocin, Banamine®. Administer drugs subcutaneously.

5. Treatment Response Protocol

Code	Condition	Treatment
1.	Mastitis	Oxytocin, penicillin, Banamine®, milk affected udder
2.	Lameness (feet)	LA 200® or Baytril®, Koportox®—Trim affected hoof
3.	Pneumonia	Baytril®, Banamine®
4.	Wounds/bites	Hydrogen Peroxide Flush, insect repellent, LA 200®, Banamine®, Starter Spray to treat maggots
5.	Leg Fracture	Banamine®, splint using stick and bandage material
6.	Eye Infection	LA 200®
7.	Reproductive Infection	Oxytocin, LA 200® <u>or</u> Baytril®, Banamine®
8.	Other	

No response in 48 hours, change antibiotic; send sick sheep home with camptender; sick guard dogs can have penicillin only.

- Banamine®--This drug is very useful in treating pain, inflammation, and toxicity due to infection. An animal that has an infection should be given antibiotics as well.

- Oxytocin®--This drug is used to increase milk letdown , aid in emptying uterus with reproductive infection, and during lambing difficulties.

- Penicillin, LA200®, and Baytril® are examples of antibiotics used to treat various infections. The choice of antibiotic used related to the needs and history of the sheep operation.

Attachment 5

Domestic Sheep Allotment Administration

Allotment Name: ______________________

Date: ______________ Time of Day: __________ Name of Observers: ______________

Start: __________

End: __________

Elevation Of Sheep: ____________

Sheep Location(s): ______________________________

GPS Location(s): ______________________________

Activity of Sheep (grazing, bedding down, moving, scattered):

____

Marker Sheep Seen: YES NO Number of Marker Sheep Observed: ______

Sheep Herder Seen: YES NO Location of Herder to Sheep: ______

Location of Sheep Herder Camp and Camp GPS Location: ______________________________

Guard Dogs Observed: YES NO Location of Guard Dogs to Sheep: ______

Number of Guard Dogs Observed: _____

Herding Dogs Observed: YES NO Location of Herding Dogs to Sheep: ______

Number of Herding Dogs Observed: _____

Other Notes and Observations: ______________________________

Weather: ______________________________

Attachment 6

Application of Risk Modeling to Domestic Sheep Allotments in Proximity to Bighorn Sheep Herd Units in the Eastern Sierra Nevada

We developed a habitat suitability model to identify habitat preferences by Sierra Nevada bighorn sheep. The model was developed using data only for rams, as they exhibit the greatest tendency to move beyond their core home ranges. The model incorporates 4,556 locations acquired from 15 GPS collared rams in the Northern (n=8), Central (n=6), and Southern (n=1) Recovery Units during May to December 2001 - 2006. May to December represents the primary period when domestic sheep are on public land allotments and also encompasses the rutting season when bighorn rams are likely to make long distance movements. We applied the model over a broad geographic region in an effort to identify the availability of areas that bighorn sheep might use during forays beyond the recovery area. The suitability model predicts habitat preferences based on elevation, slope, distance to escape terrain, terrain ruggedness, vegetation (forest-nonforest), and aspect. Next, the bighorn sheep source layer identifies the core area used by existing Sierra bighorn populations and incorporates 45,923 GPS, ground observations, and aerial telemetry locations from 28 collared bighorn rams during 2001 - 2006. The cost surface layer then combines the information on bighorn habitat preferences and their current core use areas to model the likelihood of a bighorn sheep using any particular point on the landscape within a 60 kilometer (37 miles) radius of the core area. Bighorn sheep in the Sierra Nevada have been documented to travel 53 kilometer (33 miles) from their core home range; bighorn sheep in other regions of North America have been documented to travel distances well in excess of this so the radius was rounded to 60 kilometers (37 miles) for the purposes of examining risk. This 60 kilometer (37 miles) radius does include habitat known to be populated by desert bighorn sheep.

Use data for allotments in public ownership (Humboldt-Toiyabe National Forest, Inyo National Forest, Bureau of Land Management, Mono County, and the City of Los Angeles) in proximity to the eastern Sierra Nevada was initially collected for consideration in the risk model. Allotments that fell beyond the 60 kilometer (37 miles) radius were not considered in the model. A number of other vacant or closed allotments for which use data were not available at this time were also not considered. Those allotments included Alger Lake, Bloody Canyon, Gray Hills, Green Creek, Horse Meadow, Sarman Ranch, Saroni Canal, Silver Creek, Sugarloaf, Tobacco Flat, Walters Ranch, and Wild Oat. In addition, risk values were calculated for subdivisions of allotments that occurred in closest proximity to bighorn sheep herd units; subdivisions were defined by managers or permittees based on elevation or logistical boundaries. Allotments with subdivisions included Dunderberg, Tamarack and Cameron combined, Rock Creek, and Sherwin-Deadman.

Risk in this model is determined by a combination of spatial and temporal variables associate with allotments. Spatial proximity is quantified by Mean Inverse Weighted Distance (MIWD). The temporal component was considered at two levels: permitted use and actual use. Many allotments are used for a shorter time period than is permitted by the managing agency; this reduces the risk associated with an allotment because when domestic sheep are not on the range, there is no potential for contact.

An important step in determining the risk of contact between Sierra Nevada bighorn sheep and domestic sheep is to determine where allotments occur relative to bighorn sheep on the landscape. Figure 1 illustrates the allotments and where they lie relative to their distance as it is weighted by the underlying habitat suitability. The darker red areas indicate allotments that have the least "cost" for a bighorn to move into. Figure 2 identifies the mean inverse weighted distance (MIWD) for each allotment. Mean inverse weighted distance captures a more realistic measure of spatial proximity of allotments to bighorn sheep herds in the eastern Sierra Nevada.

We determine a risk value for each allotment by calculating the product of the spatial component (MIWD) and the temporal component (the sum of the number of days grazed and the last date grazed). The risk value adjusts the risk posed by proximity by incorporating the time and date relative to the bighorn sheep rut that domestic sheep are actually using allotments (Table 1). Figures 3 -5 illustrate that many allotments that are grazed for shorter time periods and earlier in the season pose less risk than suggested simply by their proximity (Figure 2).

Clifford et al. (2007) emphasized that even with probabilities of contact between Sierra Nevada bighorn and domestic sheep as low as 2 percent per year, over a 70 year period there remains a greater than 50 percent probability of a significant disease outbreak. In the context of recovery of an endangered species, this represents a high level of risk. Data substantiating the direct transmission of respiratory pathogens between domestic sheep and bighorn sheep in the wild are lacking primarily due to the inherent logistical difficulties in obtaining the data (Martin et al. 1996 as cited in Clifford et al. 2007). The approach used to spatially model the probability of contact in the Clifford et al. (2007) model used kernel probabilities to estimate potential overlap between bighorn movements and domestic sheep allotments. Such a model can only be used to predict the likelihood of contact when a high percentage of bighorn sheep within a population are radio-collared and their movements are identified in detail. This was the case in the Northern Recovery Unit for Sierra Nevada bighorn sheep at the time the Clifford et al. (2007) model was constructed. However, this was not the case in all portions of the recovery area and such an intense level of monitoring will be expensive and difficult to maintain continuously.

Conversely, the spatial model applied in this risk assessment is based on resource selection functions and cost-weighted distances to predict the pattern of bighorn sheep use over the landscape. In contrast to the kernel distributions in the Clifford et al. (2007) model, the output of this model (combined with the temporal component) represents the relative likelihood of contact but not a probability. The benefit of this approach is that all allotments falling within the 60 kilometers (37 miles) boundary may be assessed, thus we are able to estimate larger range of variation in risk among allotments. In the Northern Recovery Unit, the allotments that fell within kernel distributions and represented a risk of contact in the Clifford et al. (2007) model also ranked the highest in this model.

Figures 3 - 5 demonstrate that the process developed by this team provides a relative ranking of risk on allotments based on the available data. Figures 3 - 5 identify allotments of highest risk on the left and allotments of relatively lower risk on the right. Figure 3 is sorted by permitted use, figures 4 and 5 are sorted by permitted use. Figure 4 includes management subdivisions of allotments, whereas figure 5 does not.

Allotment maps may be viewed at appropriate land management agency offices.

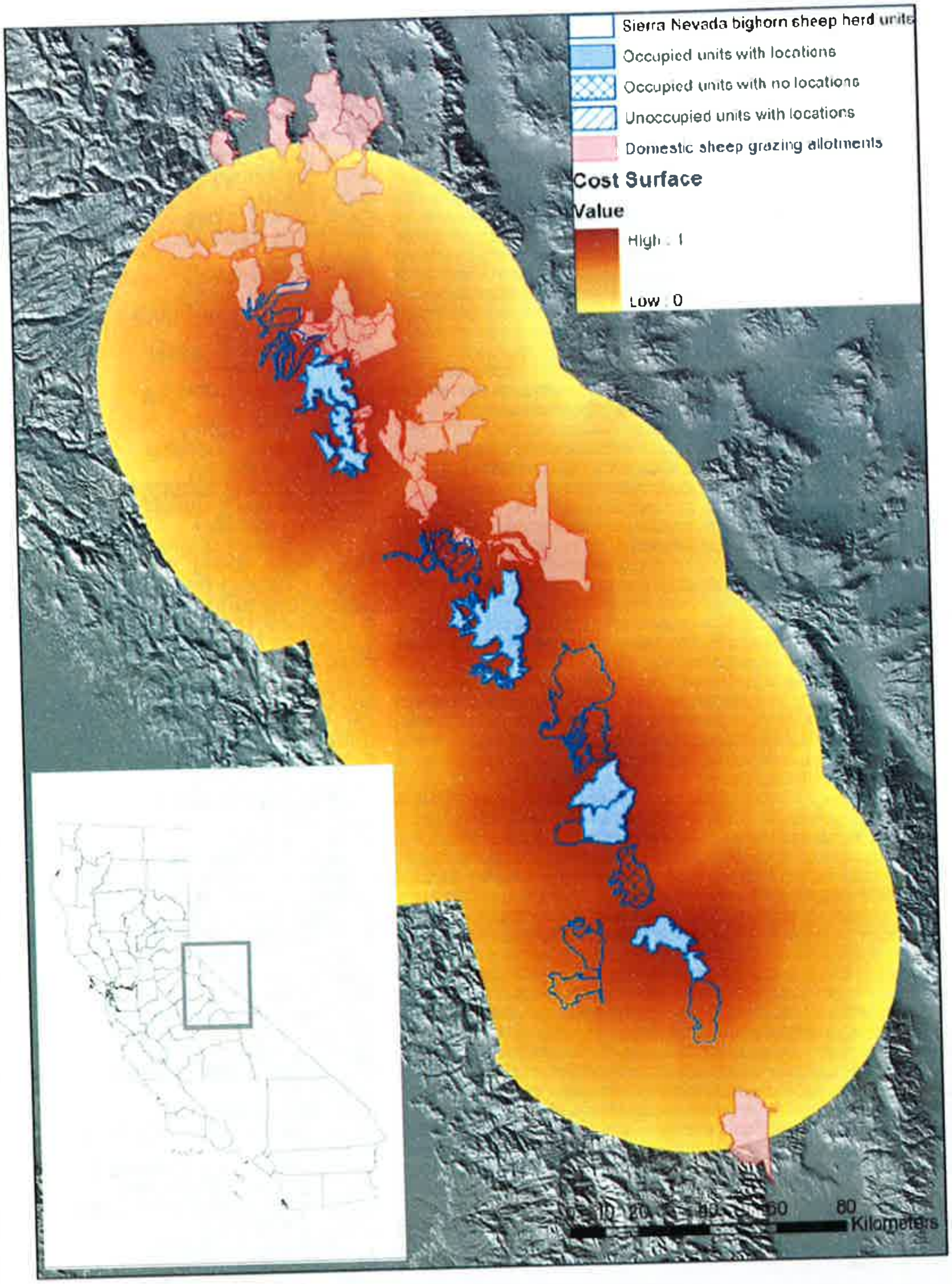


Figure 1. Inverted cost surface overlaid with the domestic sheep allotment polygons and occupied Sierra Nevada bighorn sheep herd units. The extent of the cost surface was defined to predict the maximum travel distance of Sierra Nevada bighorn sheep; the shading of the cost surface represents a decreasing likelihood of a bighorn sheep traveling that distance as the maximum extent is reached (lighter yellow).

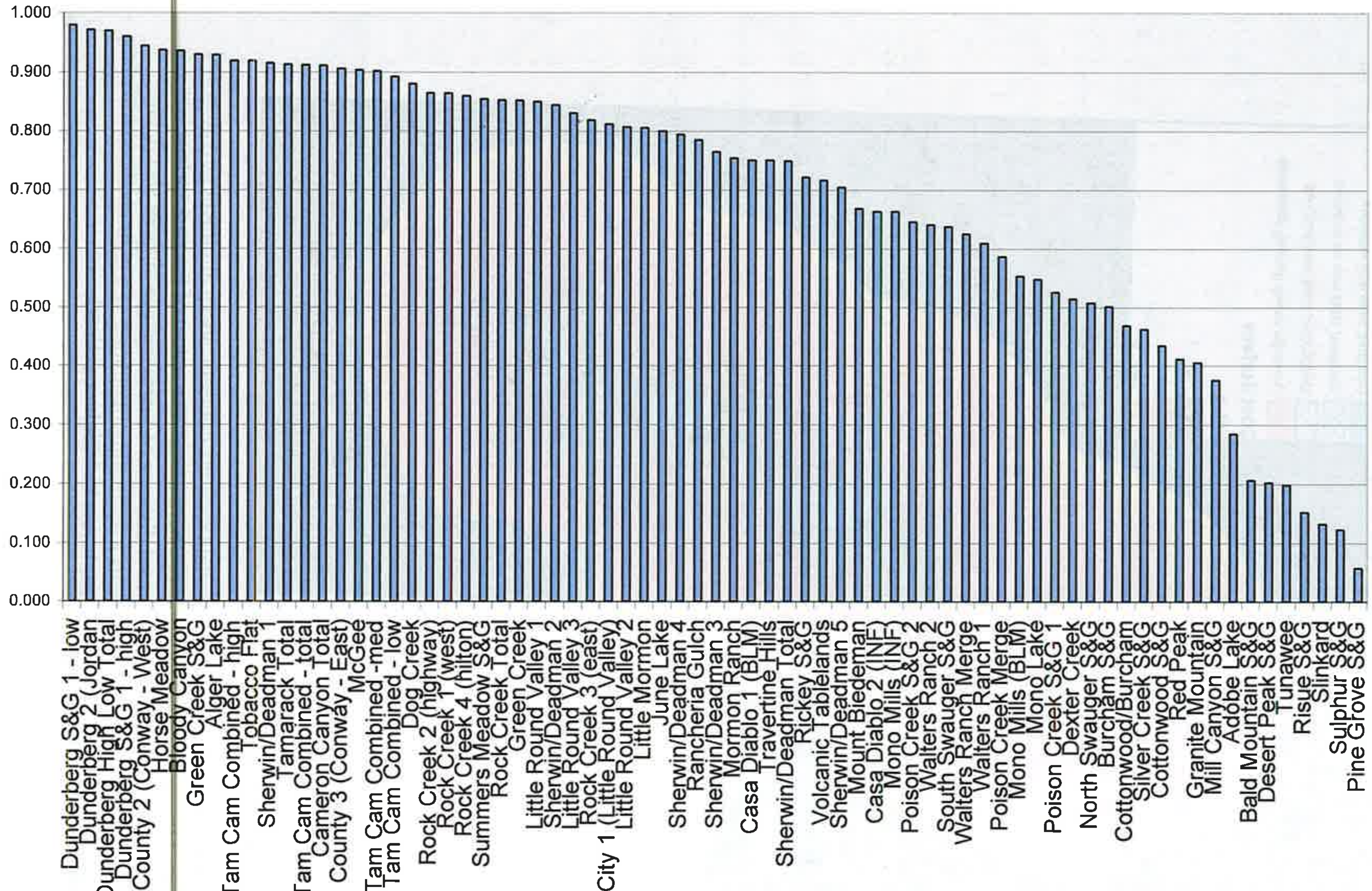


Figure 2. Mean Inverse Weighted Distance (y-axis) for each allotment (x-axis). The value represents the relative spatial proximity of domestic sheep allotments to Sierra Nevada bighorn sheep occupied habitat. Note: Cam = Cameron Canyon and Tam = Tamarack allotment.

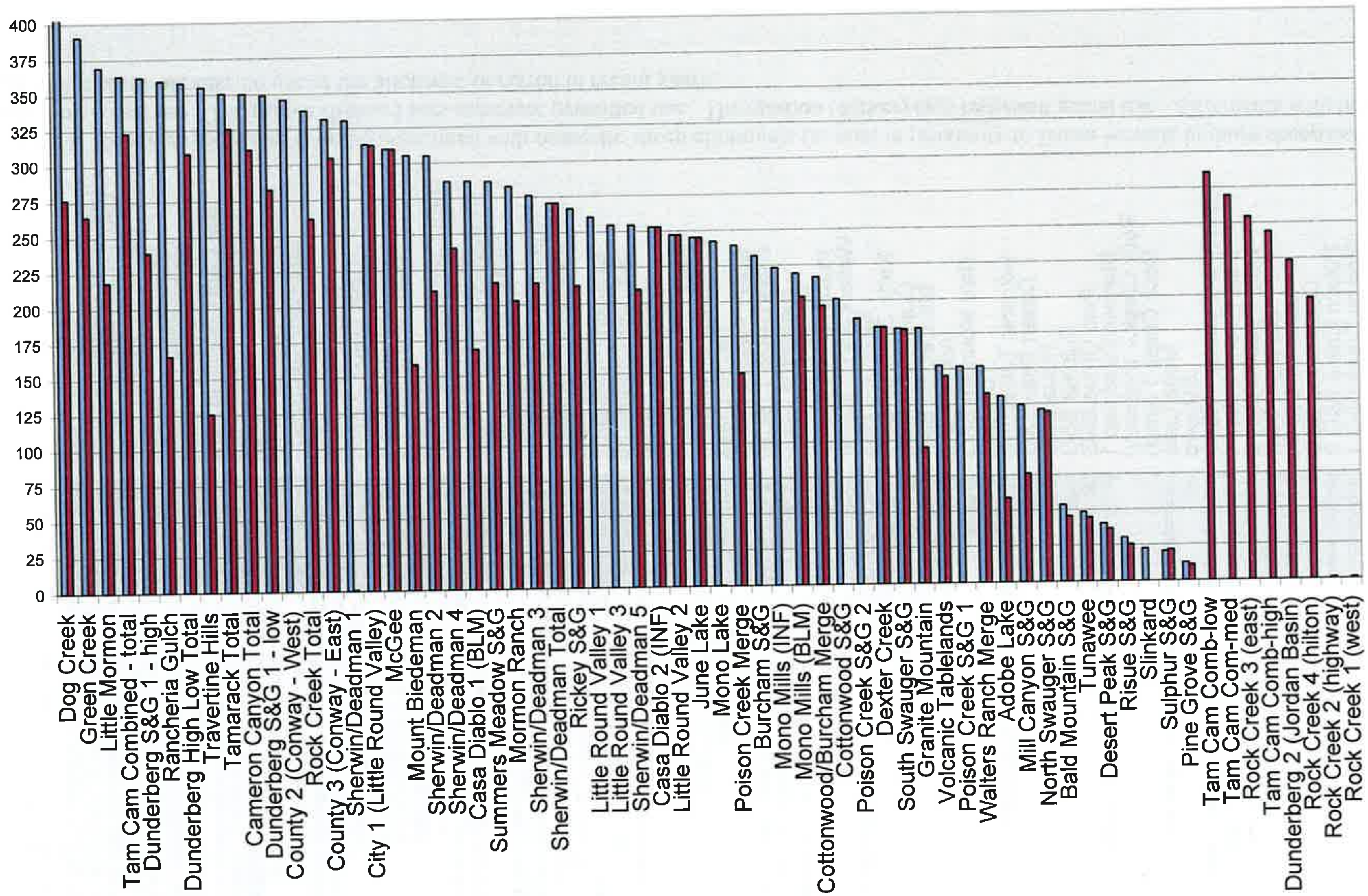


Figure 3. Relative risk values (y-axis) associated with domestic sheep allotments (x-axis) in proximity to Sierra Nevada bighorn sheep occupied habitat; sorted by permitted use. The purple (lighter) bars represent permitted use. The maroon (darker) bars represent actual use. Subunits for allotments with no value for permitted use occur because permitted use occurs for entire allotments, hence see the total allotment for permitted use. Allotments with no value permitted use occur because they have not been permitted for use in recent years.

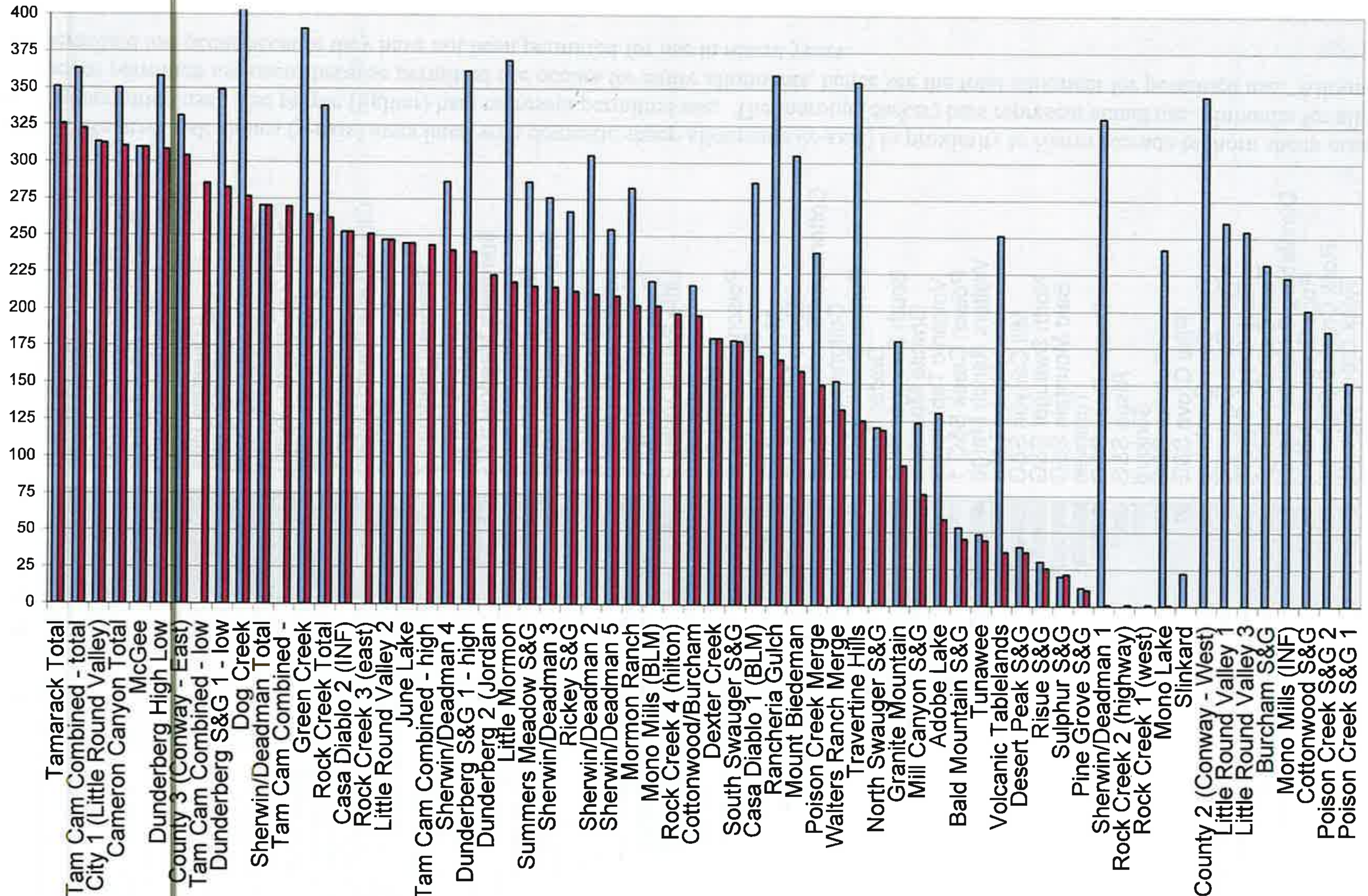


Figure 4. Relative risk values (y-axis) associated with domestic sheep allotments (x-axis) in proximity to Sierra Nevada bighorn sheep occupied habitat; sorted by actual use. The purple (lighter) bars represent permitted use. The maroon (darker) bars represent actual use. Allotments with no actual use risk value occur because no use of the allotment occurred in recent years.

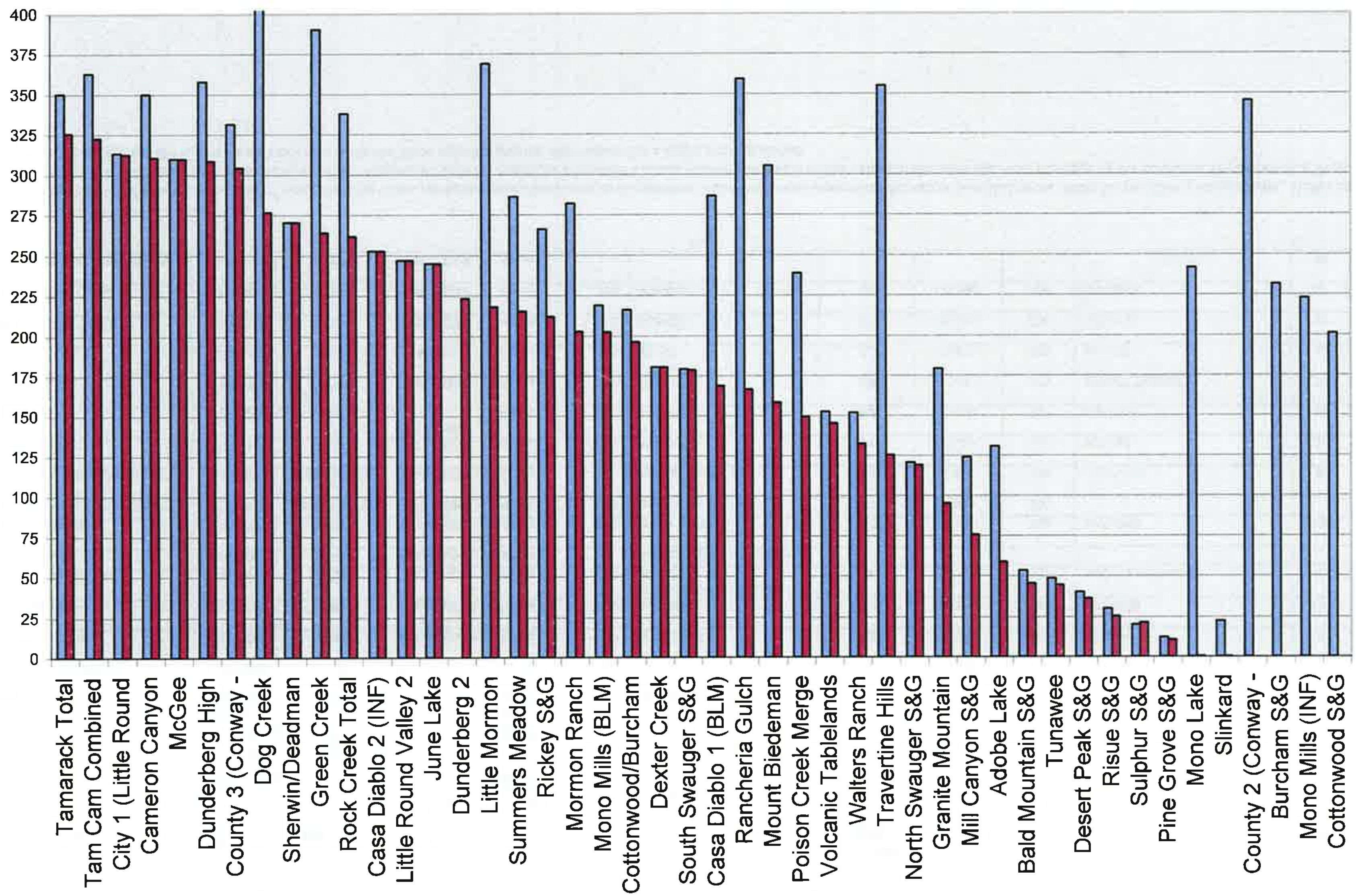


Figure 5. Relative risk values (y-axis) associated with domestic sheep allotments (x-axis) in proximity to Sierra Nevada bighorn sheep occupied habitat; sorted by actual use and excluding management subdivisions of allotments. The purple (lighter) bars represent permitted use. The maroon (darker) bars represent actual use. Allotments with no actual use risk value occur because no use of the allotment occurred in recent years.

Table 1. Domestic sheep allotments in proximity (within 60 km) to Sierra Nevada bighorn sheep habitat and associated attributes. Jurisdictional abbreviations include BLM = Bureau of Land Management, INF = Inyo National Forest, HTNF = Humboldt-Toiyabe National Forest, SNF = Stanislaus National Forest, and DWP = Los Angeles Department of Water and Power. MIWD = mean inverse weighted distance (a measure of distance adjusted by habitat suitability from bighorn locations where 1 is adjacent and 0 is distant).

NAME	AREA M2	JURISDICTION	Permittee	Status	Permitted Sheep	Permitted Dates	Total Permitted Days	Last Date	Julian Date	Max. Actual Dates	Max. Actual Days	Max. Last Date	Max. Julian Date	MEAN IWD
Adobe Lake	14243602	BLM	Indacochea	Active	99	6/1-10/31	153	31-Oct	305	7/1-7/12	12	12-Jul	194	**0.285**
Alger Lake	11881400	INF	n/a	Vacant										**0.929**
Aristo Ranch	3088699	BLM												**0.000**
Bald Mountain S&G	108427000	HTNF	F.I.M. CORP.	Active	900	5-15 to 7-15	61	15-Jul	197	6/25-7/1	37			**0.207**
Bloody Canyon	22265500	INF	n/a	Vacant										**0.936**
Burcham S&G	40592500	HTNF	F.I.M. CORP.	Active		See combined w/ Cottonwood								**0.501**
Cameron Canyon S&G Total	17057200	HTNF	F.I.M. CORP.	Active	900	6/28-9/30, 10/1-10/15	95	15-Oct	289	7/10-9/22	75	22-Sep	266	**0.911**
Casa Diablo 1 (BLM)	203150000	BLM	Ansolabehere	Active	57	6/15 to 9/30	108	30-Sep	274	8/1-8/6	6	6-Aug	219	**0.750**
Casa Diablo 2 (INF)	12784300	INF	Ansolabehere	Active	3500	6/15-9/30	107	30-Sep	274	6/15-9/30	107	30-Sep	274	**0.665**
City 1 (Little Round Valley)	3576810	DWP	Echenique	Active	1000	20-25 May-5 July, 20-sep - 28-oct	84	28-Oct	302	5/20-7/5, 9/20-10/28	83	28-Oct	302	**0.812**
Cottonwood S&G	54833000	HTNF	F.I.M. CORP.	Active		See combined w/ Burcham								**0.435**
Cottonwood/Burcham	95425500	HTNF	F.I.M. CORP.	Active	900	6/15 - 10/25	163	25-Oct	299	6/18-9/19	156	19-Sep	263	**0.468**
County 2 (Conway Ranch - West)	1044910	Mono County	F.I.M. CORP.	Active	1000	approx. 1-sep - 1-nov	60	1-Nov	306					**0.944**
County 3 (Conway Ranch - East)	3592200	Mono County	F.I.M. CORP.	Active		approx. 1-sep - 1-nov	60	1-Nov	306	~10/1-11/1	30	1-Nov	306	**0.905**
Desert Peak S&G	75385700	HTNF	F.I.M. CORP.	Active	1025	5/16-6/15	31	15-Jun	167	5/15-6/6	22	6-Jun	158	**0.202**
Dexter Creek	75959500	INF	I&M Sheep Co.	Active	1500	6/15-9/15	92	15-Sep	259	6/15-9/15	92	15-Sep	259	**0.514**
Dog Creek[1]	31060900	BLM	F.I.M. CORP.	Active	985	6/1-10-31	153	31-Oct	305	6/5-6/17,6/30-8/28	73	29-Aug	242	**0.881**
Dry Canyon	3684088	BLM	Borda	Active	51	3/1-5/31	92	31-May	152	4/1-4/20	20	20-April	111	**0.000**
Dunderberg S&G 1 - high	8262746	HTNF	F.I.M. CORP.	Active	900	6/28-9/30	95	30-Sep	274	7/25-8/12	19	12-Aug	225	**0.960**
Dunderberg S&G 1 - low	13153824	HTNF	F.I.M. CORP.	Active	900	6/28-9/30	95	30-Sep	274	8/13-9/18	37	18-Sep	262	**0.980**
Dunderberg S&G 2 (Jordan Basin)	5720541	HTNF	F.I.M. CORP.	Active						7/1-7/24	24	24-Jul	206	**0.971**

[1] "Max Actual Dates" and "Max Actual Days" value for Dog Creek are based on discussions with the permitte, but are not consistenet with the values provided by the BLM for the 2006 grazing season. BLMs records indicate "Max Actual Dates" of 7/20-8/29 and "Max Actual Days" of 41. Figures 3-5 (above) depict the allotment's actual relative risk based on the values in the table that were provided by the permittee. Descrepency is likely a result of the permittee reporting typical use over a number of years while the BLM reported grazing information for a single grazing season.

Dunderberg S&G High Low Total	21416570	HTNF	F.I.M. CORP.	Active	900	6/28-9/30	95	30-Sep	274	7/25-9/18	56	18-Sep	262	**0.970**
Granite Mountain	85830648	BLM	Indacochea	Active	845	7/1-10/15	153	15-Oct	289	7/12-8/1	21	1-Aug	214	**0.405**
Gray Hills S&G	14961400	HTNF	E.L.W. Ranches Inc.	Active	1650	4/3-4/2 nte 1695 sm	41							**0.000**
Green Creek[2]	17737000	BLM	I&M SHEEP CO.	Active	607	1-Jun to 31 Oct	153	31-Oct	305	7/1-9/15	51	15-Sep	259	**0.852**
Green Creek S&G	5279280	HTNF	n/a	Vacant										**0.929**
Horse Meadow	8717560	INF	n/a	Vacant										**0.937**
June Lake	66876800	INF	I&M Sheep Co.	Active	1500	7/1-8/31	62	31-Aug	244	7/1-8/31	62	31-Aug	244	**0.800**
Little Mormon	40363300	BLM	F.I.M. CORP.	Active	2981	6/1-10/31	153	31-Oct	305	6/1-7/20	50	20-Jul	202	**0.805**
Little Round Valley 1 (North)	3351920	BLM	Echenique	Active	Pt. of LRV	5-Oct - 18 Oct	14	18-Oct	292	7/8 – 7/27	20	NA	209	**0.850**
Little Round Valley 2	3470780	BLM	Echenique	Active	1400	5-Oct - 18 Oct	14	18-Oct	292	10/5-10/18	14	18-Oct	292	**0.807**
Little Round Valley 3 (South)	637036	BLM	Echenique	Active	Pt. of LRV	5-Oct – 18 Oct	14	18-Oct	292					**0.831**
McGee	17295700	INF	Ansolabehere	Active	1600	6/07-9/07	92	7-Sep	251	6/07-9/07	92	7-Sep	251	**0.903**
Mill Canyon S&G	30930000	HTNF	F.I.M. CORP.	Active	1025	6/1-6/25	25	31-Oct	305	6/1-6/25	25	25-Jun	177	**0.375**
Mono Lake	35774900	BLM	Indacochea	Active	763	1-Jul to 15 Oct	153	15-Oct	289	8/1 – 8/15	15	15-Aug	228	**0.547**
Mono Mills (BLM)	118311000	BLM	I&M SHEEP CO.	Active	3045	1-Jul - 15-Oct	107	15-Oct	289	7/1-9/30	92	30-Sep	274	**0.553**
Mono Mills (INF)	138152000	INF	Etchegeray	Active	4000	7/01-9/15	77	15-Sep	259					**0.663**
Mormon Ranch	13432500	BLM	I&M SHEEP CO.	Active	582	22-Jul - 15 Oct	86	15-Oct	289	7/22-8/23	33	23-Aug	236	**0.754**
Mount Biedeman	20044800	BLM	F.I.M. CORP.	Active	507	6/1-10/31	153	31-Oct	305	6/1-6/15, 6/23-7/16	39	16-Jul	198	**0.668**
North Swauger S&G	21670300	HTNF	I&M Sheep Co.	Active	1200	7/27-8/10	15	10-Aug	223	7/22-8/6	16	6-Aug	219	**0.507**
Pine Grove S&G	69288200	HTNF	F.I.M. CORP.	Active	900	5/25-6/27	34	27-Jun	179	6/12-6/24	13	24-Jun	176	**0.057**
Poison Creek Merge	105954630	HTNF	F.I.M. CORP.	Active	1025	6/19-10-15	119	15-Oct	289	6/26-8/3	39	3-Aug	216	**0.585**
Poison Creek S&G 1	4480630	HTNF	F.I.M. CORP.	Active		See merge		15-Oct	289					**0.525**
Poison Creek S&G 2	101474000	HTNF	F.I.M. CORP.	Active		See merge		15-Oct	289					**0.646**
Rancheria Gulch	102571000	BLM	F.I.M. CORP.	Active	1590	1-Jun to 31 Oct	153	31-Oct	305	6/1-6/30	30	30-Jun	182	**0.784**
Red Peak	70200000	SNF		Active										**0.412**
Rickey S&G	28428900	HTNF	F.I.M. CORP.	Active	900	6/28-9/30	95	30-Sep	274	7/25-9/6	44	6-Sep	250	**0.722**
Risue S&G	52462700	HTNF	F.I.M. CORP.	Active	1025	4/16-5/31	46	31-May	152	5/16-5/31	16	31-May	152	**0.152**
Rock Creek 1 (west)	16661300	INF	Echenique	Active	1250	6/1-9/30					0			**0.864**

[2] "Max Actual Dates", "Max Actual Days", "Max Last Date", and "Max Julian Date" values for Green Creek are based on discussions with the permitte, but are not consistenet with the values provided by the BLM for the 2006 grazing season. BLMs records indicate "Max Actual Dates" of 7/1-8/10; "Max Actual Days" of 41; "Max Last Date" of 10-August; and "Max Julian Date" of 223. Figures 3-5 (above) depict the allotment's actual relative risk based on the values in the table that were provided by the permittee. Descrepency is likely a result of the permittee reporting typical use over a number of years while the BLM reported grazing information for a single grazing season.

Rock Creek 2 (highway)	4296790	INF	Echenique	Active		6/1-9/30					0			**0.865**
Rock Creek 3 (east)	24696500	INF	Echenique	Active		6/1-9/30	122	30-Sep	274	5/31-8/6	68	6-Aug	219	**0.819**
Rock Creek 4 (hilton)	5164700	INF	Echenique	Active		6/1-9/30	122	30-Sep	274	7/8-7/27	20	27-Jul	209	**0.860**
Rock Creek Tota	50819290	HTNF	Echenique	Active	1250	6/1-9/30	122	30-Sep	274	5/31-8/6	88	6-Aug	219	**0.853**
Saroni Canal S&G	32163100	HTNF	F.I.M. CORP.	Active	1025	4/1-5/18	48	18-May	139	4/28-5/15	18	15-May	136	**0.000**
Sherwin/Deadman 1	3929960	INF	Echenique	Active	2600	7/05-9/30	87	30-Sep	274		0	1-Jan	001	**0.915**
Sherwin/Deadman 2	24422000	INF	Echenique	Active	2600	7/05-9/30	87	30-Sep	274	7/30-8/17	19	17-Aug	230	**0.844**
Sherwin/Deadman 3	20384300	INF	Echenique	Active	2600	7/05-9/30	87	30-Sep	274	8/18-9/12	25	12-Sep	256	**0.764**
Sherwin/Deadman 4	35580000	INF	Echenique	Active	2600	7/05-9/30	87	30-Sep	274	9/17-10/2	26	2-Oct	276	**0.794**
Sherwin/Deadman 5	36063900	INF	Echenique	Active	2600	7/05-9/30	87	30-Sep	274	8/19-9/19	34	19-Sep	263	**0.704**
Sherwin/Deadman Total	120380160	INF	Echenique	Active	2600	7/05-9/30	87	30-Sep	274	7/30-9/30	87	30 Sep	274	**0.749**
Silver Creek S&G	78331500	HTNF	N/A	Vacant										**0.462**
Slinkard	50691800	BLM	F.I.M. CORP.	Active	670	5/15-5/31	17	31-May	152		0			**0.132**
South Swauger S&G	35001900	HTNF	I&M SHEEP CO.	Active	1200	7/6-7/26 & 8/11-8/28	40	28-Aug	241	7/1-7/21, 8/7-8/27	40	27-Aug	240	**0.637**
Sugarloaf S&G	56030100	HTNF	F.I.M. CORP.	Active	1800	16/16-2/28 (not to exceed 35d)	35	28-Feb	059					**0.000**
Sulphur S&G	205543000	HTNF	F.I.M. CORP.	Active	1025	12/16-3/15 (not to exceed 35d), 4/10-5/20,4/10-4/22	89	15-Mar	075	4/17-5/15	39	15-May	136	**0.122**
Summers Meadow S&G	9982230	HTNF	Borda Land & Sheep Co.	Active	2000	6/16-10/31 nte 1172 sm	30	31-Oct	305	7/21-8/14	25	14-Aug	227	**0.855**
Tamarack & Cameron Combined - high	9415872	HTNF	F.I.M. CORP.	Active						6/19-9/21		21-Sep	265	**0.919**
Tamarack & Cameron Combined - low	7672993	HTNF	F.I.M. CORP.	Active						6/19-9/21	55	21-Sep	265	**0.892**
Tamarack & Cameron Combined - med	16600632	HTNF	F.I.M. CORP.	Active						6/19-9/21	34	21-Sep	265	**0.901**
Tamarack & Cameron Combined - total	41229500	HTNF	F.I.M. CORP.	Active	1025	6/28-9/30, 10/1-10/15	109	15-Oct	289	6/19-9/21	89	21-Sep	265	**0.912**
Tamarack Total	24172300	HTNF	F.I.M. CORP.	Active	1650	6/28-9/30, 10/1-10/15	95	15-Oct	289	7/10-9/30	83	30-Sep	274	**0.912**
Travertine Hills	42882400	BLM	F.I.M. CORP.	Active	670	17-May - 31-Oct	168	31-Oct	305	5/17-5/31	15	31-May	152	**0.750**
Tunawee	226600000	BLM	Echinique	Active	3040	3/1 – 5/31	92	31-May	152	3/20-5/31	72	31-May	152	**0.199**
Volcanic Tablelands	190820000	BLM	Ansolabehere	Active	1010	1-May - 15-Jun	46	15-Jun	167	5/20-6/15	27	15-Jun	167	**0.716**
Walters Ranch 1	1941890	BLM												**0.609**
Walters Ranch 2	160755	BLM												**0.640**
Walters Ranch Merge	2102645	BLM	I&M SHEEP CO.	Active	452	5/1-6/30	61	30-Jun	182	6/1-6/30	30	30-Jun	182	**0.625**
Wild Oat S&G 1	101755	HTNF	F.I.M. CORP.	Active										**0.000**
Wild Oat S&G 2	10745000	HTNF	F.I.M. CORP.	Active										**0.000**

Wild Oat S&G Merge	10846755	HTNF	F.I.M. CORP.	Active	1650	4/1-7/15 (not to exceed 24 d)	24			8/12-8/14	3	31-Jul	213	**0.000**

Note: In rare cases, the number of actual days that an allotment was used is the sum of days for 2 separate bands of sheep using different areas of an allotment.