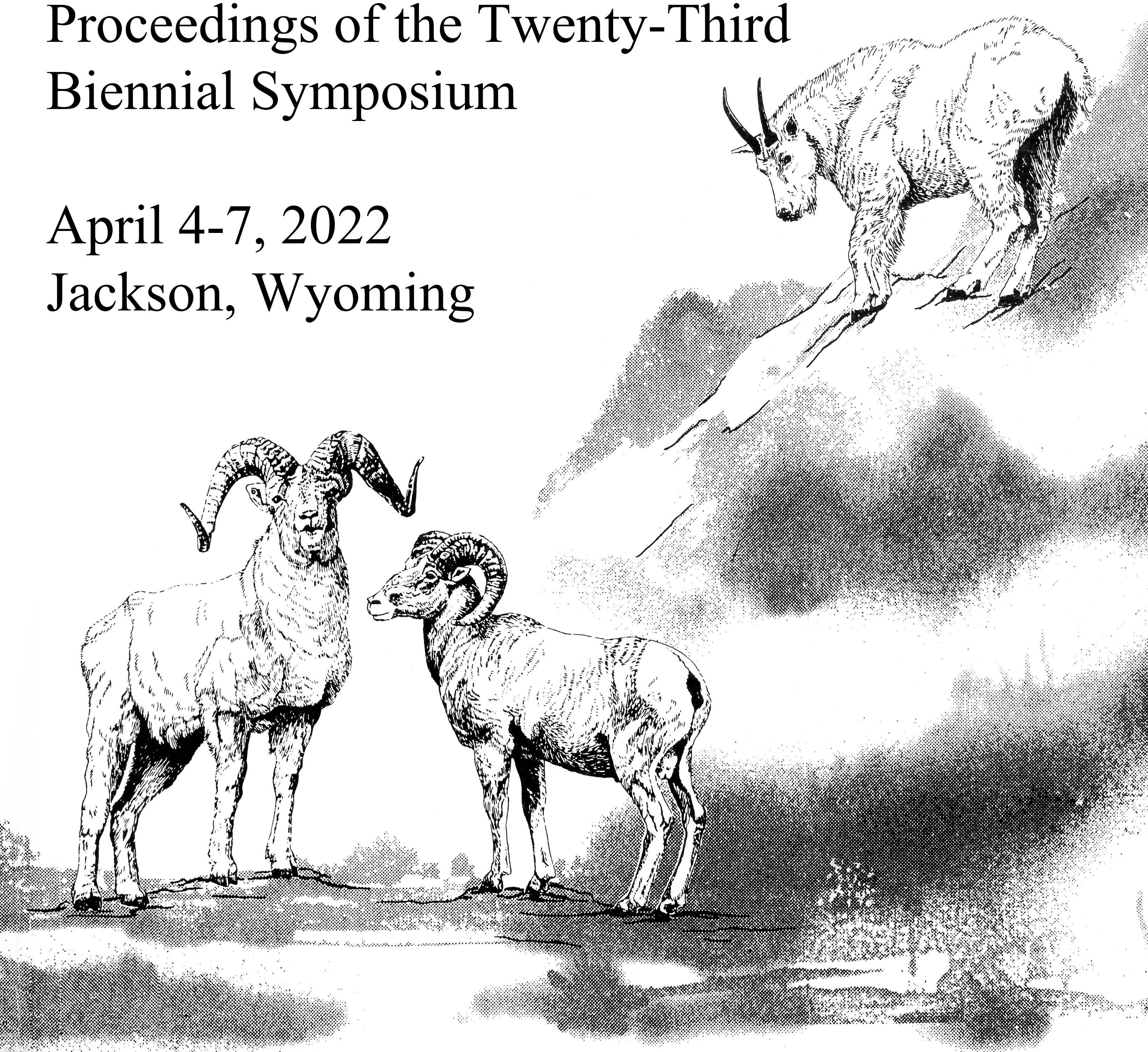
Northern Wild Sheep and Goat Council

Proceedings of the Twenty-Third Biennial Symposium

April 4-7, 2022
Jackson, Wyoming



Northern Wild Sheep and Goat Council

PROCEEDINGS OF THE 23rd BIENNIAL SYMPOSIUM

APRIL 4-7, 2022
JACKSON, WYOMING

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Northern Wild Sheep and Goat Council

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Northern Wild Sheep and Goat Council

NORTHERN WILD SHEEP AND GOAT COUNCIL SYMPOSIA

Date	Symposium	Location	Symposium Coordinator/Chair	Proceedings Editor(s)	NWSGC Executive Director
May 26-28, 1970	NWSC 1	Williams Lake, BC	Harold Mitchell		
April 14-15, 1971	NAWSC 1	Fort Collins, CO	Eugene Decker/Wayne Sandfort	Eugene Decker	
April 11-13, 1972	NWSC 2	Hinton, AB	E.G. Scheffler		
April 23-25, 1974	NWSC 3	Great Falls, MT	Kerry Constan/James Mitchell		
Feb. 10-12, 1976	NWSC 4	Jackson, WY	E. Tom Thorne		
April 2-4, 1978	NWSGC 1	Penticton, BC	Daryll Hebert/M. Nation	Daryll Hebert/M. Nation	
April 23-25, 1980	NWSGC 2	Salmon, ID	Bill Hickey		
March 17-19, 1982	NWSGC 3	Fort Collins, CO	Gene Schoonveld	James Bailey/Gene Schooneveld	
Apr. 30-May 3, 1984	NWSGC 4	Whitehorse, YK	Manfred Hoefs	Manfred Hoefs	Wayne Heimer
April 14-17, 1986	NWSGC 5	Missoula, MT	Jerry Brown	Gayle Joslin	Wayne Heimer
April 11-15, 1988	NWSGC 6	Banff, AB	Bill Wishart	Bill Samuel	Wayne Heimer
May 14-18, 1990	NWSGC 7	Clarkston, WA	Lloyd Oldenburg	James Bailey	Wayne Heimer
Apr. 27-May 1, 1992	NWSGC 8	Cody, WY	Kevin Hurley	John Emmerich/Bill Hepworth	Wayne Heimer
May 2-6, 1994	NWSGC 9	Cranbrook, BC	Anna Fontana	Margo Pybus/Bill Wishart	Kevin Hurley
Apr. 30-May 3, 1996	NWSGC 10	Silverthorne, CO	Dale Reed	Kevin Hurley/Dale Reed/Nancy Wild (compilers)	Kevin Hurley
April 16-20, 1998	NWSGC 11	Whitefish, MT	John McCarthy	John McCarthy/Richard Harris/Fay Moore (compilers)	Kevin Hurley
May 31-June 4, 2000	NWSGC 12	Whitehorse, YK	Jean Carey	Jean Carey	Kevin Hurley
April 23-27, 2002	NWSGC 13	Rapid City, SD	Ted Benzon	Gary Brundige	Kevin Hurley
May 15-22, 2004	NWSGC 14	Coastal Alaska	Wayne Heimer	Wayne Heimer/Dale Toweill/Kevin Hurley	Kevin Hurley
April 2-6, 2006	NWSGC 15	Kananaskis, AB	Jon Jorgenson	Margo Pybus/Bill Wishart	Kevin Hurley
Apr. 27-May 1, 2008	NWSGC 16	Midway, UT	Anis Aoude	Tom Smith	Kevin Hurley
June 7-11, 2010	NWSGC 17	Hood River, OR	Craig Foster	Vern Bleich	Kevin Hurley
March 12-15, 2012	NWSGC 18	Kamloops, BC	Steve Gordon/Steve Wilson/Mari Wood	Steve Wilson/Mari Wood	Kevin Hurley
June 2-5, 2014	NWSGC 19	Fort Collins, CO	Janet George	Bruce Watkins, Ricki Watkins	Kevin Hurley

Northern Wild Sheep and Goat Council

NORTHERN WILD SHEEP AND GOAT COUNCIL SYMPOSIA (Cont'd)

Date	Symposium	Location	Symposium Coordinator/Chair	Proceedings Editor(s)	NWSGC Executive Director
May 9-12, 2016	NWSGC 20	Moscow, ID Pullman, WA	Hollie Miyasaki,/Rich Harris/David Smith	Rich Harris	Kevin Hurley
May 21-24, 2018	NWSGC 21	Whitefish, MT	Brent Lonner/Bruce Sterling/Caryn Dearing	Justin Gude	Kevin Hurley
November 3-5, 2020	NWSGC 22	Alberta (virtual)	Beth MacCallum	Kathreen Ruckstuhl	Kevin Hurley
April 4-7, 2022	NWSGC 23	Jackson, WY	Doug McWhirter	Doug McWhirter, Alyson Courtemanch, Peach Van Wick	Kevin Hurley

Northern Wild Sheep and Goat Council

GUIDELINES OF THE NORTHERN WILD SHEEP AND GOAT COUNCIL

The purpose of the Northern Wild Sheep and Goat Council is to foster wise management and conservation of northern wild sheep and goat populations and their habitats.

This purpose will be achieved by:

1) Providing for timely exchange of research and management information;
2) Promoting high standards in research and management; and
3) Providing professional advice on issues involving wild sheep and goat conservation and management.

I. The membership shall include professional research and management biologists and others active in the conservation of wild sheep and goats. Membership in the Council will be achieved either by registering at, or purchasing proceedings of, the biennial conference. Only members may vote at the biennial meeting.

II. The affairs of the Council will be conducted by an Executive Committee consisting of: three elected members from Canada; three elected members from the United States; one ad hoc member from the state, province, or territory hosting the biennial meeting; and the past chairperson of the Executive Committee. The Executive Committee elects its chairperson.

III. Members of the Council will be nominated and elected to the executive committee at the biennial meeting. Executive Committee members, excluding the ad hoc member, will serve for four years, with alternating election of two persons and one person of each country, respectively. The ad hoc member will only serve for two years.

The biennial meeting of members of the Council shall include a symposium and business meeting. The location of the biennial meeting shall rotate among the members' provinces, territories and states. Members in the host state, province or territory will plan, publicize and conduct the symposium and meeting; will handle its financial matters; and will prepare and distribute the proceedings of the symposium.

The symposium may include presentations, panel discussions, poster sessions, and field trips related to research and management of wild sheep, mountain goats, and related species. Should any member's proposal for presenting a paper at the symposium be rejected by members of the host province, territory or state, the rejected member may appeal to the Council's executive committee. Subsequently, the committee will make its recommendations to the members of the host state, territory or province for a final decision.

The symposium proceedings shall be numbered with 1978 being No. 1, 1980 being No. 2, etc. The members in the province, territory or state hosting the biennial meeting shall select the editor(s) of the proceedings. Responsibility for quality of the proceedings shall rest with the editor(s). The editors shall strive for uniformity of manuscript style and printing, both within and among proceedings.

The proceedings shall include edited papers from presentations, panel discussions or posters given at the symposium. Full papers will be emphasized in the proceedings. The editor will set a deadline for submission of manuscripts.

Members of the host province, territory, or state shall distribute copies of the proceedings to members and other purchasers. In addition, funds will be solicited for distributing a copy to each major wildlife library within the Council's states, provinces, and territories.

IV. Resolutions on issues involving conservation and management of wild sheep and goats will be received by the chairperson of the Executive Committee before the biennial meeting. The Executive Committee will review all resolutions, and present them with recommendations at the business meeting. Resolutions will be adopted by a plurality vote. The Executive Committee may also adopt resolutions on behalf of the Council between biennial meetings.

V. Changes in these guidelines may be accomplished by plurality vote at the biennial meeting.

FOREWORD

The manuscripts and abstracts included in these proceedings were presented during the 23rd Biennial Symposium of the Northern Wild Sheep and Goat Council, held April 4-7, 2022 at the Snow King Resort and Hotel in Jackson, Wyoming.

Thanks and appreciation must be given to symposium sponsors and participants. In addition, Conference Chair Doug McWhirter, and Coordinating Committee members Melanie Barnum, Alyson Courtemanch, and Ben Wise, and Session Moderators Sarah Dewey, Peach Van Wick, Tony Mong, Hank Edwards, Carson Butler, Alyson Courtemanch, Ben Wise, and Doug McWhirter must be recognized for their contributions. Thanks must also be given to Grand Teton National Park Chief of Staff Jeremy Barnum, and Chief of Science and Resource Management Gus Smith, as well as U.S. Fish and Wildlife Service/National Elk Refuge Manager Frank Durbian, and Wildlife Biologist Eric Cole.

All manuscripts were peer-edited by Doug McWhirter, Alyson Courtemanch, and Peach Van Wick prior to publication. Suggested editorial comments were provided to each senior author; senior authors had opportunity(ies) to accept or reject suggested edits prior to submission of their final manuscripts. Formatted page groofs were forwarded to respective senior authors prior to inclusion into the final proceedings. Final content, particularly verification of literature citations, is the responsibility of the authors. In instances where data presented at the symposium is, or will be published in other peer-reviewed journals, only the presentation abstract has been presented here.

While NWSGC strives for professional, scientific presentations at our symposia, followed up with quality manuscripts for our proceedings, NWSGC Guidelines do not rigidly specify format, minimum data requirement, or thresholds of statistical analyses for subsequently included manuscripts. Thus, NWSGC Proceedings <u>may</u> contain manuscripts that are more opinion-based than data- or fact-based; critical evaluation of information presented in these proceedings is the responsibility of subsequent readers.

Kevin Hurley
NWSGC Executive Director
September 1, 2023

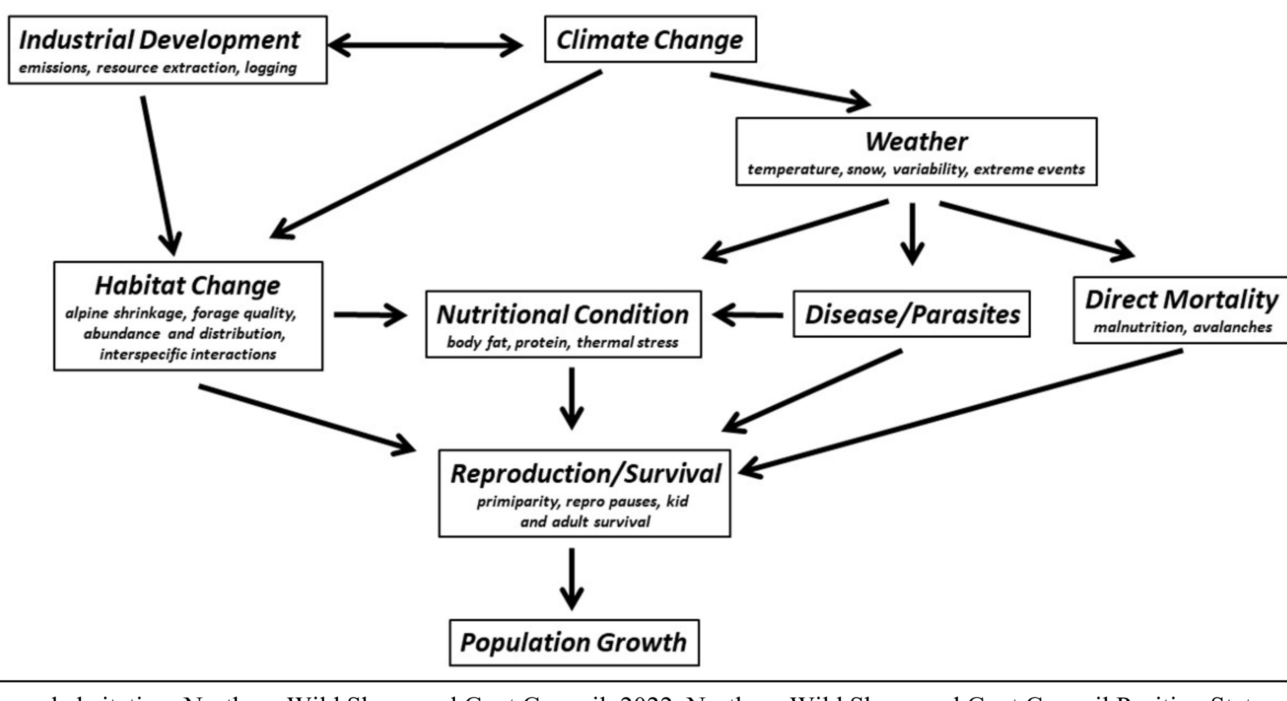
NORTHERN WILD SHEEP AND GOAT COUNCIL POSITION STATEMENT

IMPACTS OF CLIMATE CHANGE ON MOUNTAIN GOATS AND THEIR HABITATS: CONSIDERATIONS FOR CONSERVATION, MANAGEMENT AND MITIGATION

Executive summary:

Extensive evidence from long-term climate data has led to clear scientific consensus that global climate is changing as a result of human activities. Within this broader context, climate change is occurring more rapidly in many high-elevation alpine and mountain ecosystems, than elsewhere. Mountain goats (*Oreamnos americanus*) are an iconic and highly valued species of western North American mountain ecosystems and, due to specialized adaptations for life in cold, mountainous environments, are particularly sensitive to changes in weather and climate (Figure 1). As a consequence, mountain goats are considered "sentinels" of the ecological effects and conservation challenges associated with climate change. Effects of climate change are likely to be negative in many instances and represent impacts that add to existing threats to the species (such as human disturbance, hunting, disease, predation).

Figure 1. Diagram illustrating relationships between climate change and other factors influencing mountain goat population ecology.



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In mountain goat range, climate (defined as average weather patterns over a 30+ year period) is likely to change in three principal ways: summer and winter temperatures are expected to increase, winter precipitation is also predicted to increase but due to winter warming result in overall less snow (but more rain-on-snow events), and weather is expected to become more spatially and temporally variable including more extreme events (summer heat waves, extreme winter snowfall and/or warming rain events). Because of the broad geographic range of mountain goats, future changes to climate and weather are likely to differ depending upon locality. Summer warming is expected to exacerbate thermal physiological stress, reduce persistence of thermal refugia (snow patches), shorten vegetation green-up, negatively impact forage quality, and shrink alpine habitats due to treeline advance leading to habitat loss and reduced connectivity between mountain goat populations. Although less winter snowfall may be beneficial in some instances, increased prevalence of rain-on-snow events can be detrimental by burying forage under hard crusts, creating hazardous icing conditions along trails in escape terrain, or increasing avalanche-risk through potential changes in avalanche character. Extreme events can be of major demographic significance when negative and have been documented to cause population declines of over 25% annually. In contrast, positive extreme events may result in relatively modest demographic benefits due to the low intrinsic growth potential of mountain goat populations (i.e. 1-4% annually). Consequently, when extreme events are negative, demographic recovery times may take many years, even if followed by favorable conditions.

Changes in climate will necessitate re-examination and modification of mountain goat monitoring, management and conservation strategies. Expected additive effects of climate change will likely require more conservative management practices including more restrictive harvest practices, habitat manipulation, and adopting mitigation strategies to minimize commercial and recreational disturbance. Due to increasing climate-linked impacts, mountain goat population and habitat monitoring efforts must be increased to document changes, so timely management interventions can be implemented. Conventional monitoring techniques may also need to be re-evaluated and modified, to ensure they remain effective to rigorously detect population change, given predicted changes in seasonal conditions that influence survey detectability. Collection of data related to climate and climate-sensitive metrics will be increasingly important for determining causality and partitioning effects driving mountain goat population changes. Further research is urgently needed to refine our ability to understand and predict how climate change will influence mountain goat populations at the individual-level and at local, regional, and range-wide scales. There is also a pressing need to improve our understanding of baseline conditions in many geographic areas in relation to disease and parasite prevalence, mountain goat population status, habitat conditions, inter-specific interactions including predator-prey dynamics and if there are different responses between native and introduced populations.

1. Project background, objectives and intended applications

In 2022, the Northern Wild Sheep and Goat Council (NWSGC) formally acknowledged and implemented an effort to develop this position statement focused on managing and mitigating the impacts of climate change on mountain goats and their habitats. To accomplish this task, the NWSGC convened a working group composed of 15 subject matter experts from across North America and developed this position statement with the intent to represent the current scientific consensus regarding climate change effects on mountain goats and associated conservation implications. Specifically, the purpose of this position statement is to: 1) document the state of knowledge regarding climate change in mountain environments and associated effects on mountain goats and their habitats, 2) provide expert guidance to agencies, non-governmental organizations (NGOs), conservation stakeholders and other interested parties, 3) develop communication material suitable for the public to improve their understanding of these challenges, and 4) identify management and conservation strategies to respond to and mitigate projected changes to mountain goats and their habitats. This position statement has been reviewed by the NWSGC Executive Committee, and endorsed by the NWSGC membership prior to formal adoption and publication.

2. Synthesis of knowledge

a. Climate change in western North American mountain environments

Extensive evidence from long-term climate data has led to clear scientific consensus that global climate is changing as a result of human activities (Intergovernmental Panel on Climate Change 2021, World Meteorological Organization 2022). Within this broader context, change is occurring more rapidly in high-elevation alpine and mountain ecosystems than elsewhere (Diaz et al. 2003, Pepin et al. 2022). The process for which disproportionate effects occur at higher elevation (termed “alpine amplification”) is mediated by positive-feedback dynamics driven by increased heat absorption when snow cover and albedo (i.e. reflection of light and heat away from the earth’s surface) are reduced. In addition, changes in atmospheric circulation patterns drive heat-flux poleward; a secondary process that leads to an additive effect in northern mountain regions (Mountain Research Initiative EDW Working Group 2015, Pepin et al. 2022). As a result, mountain regions, including those inhabited by mountain goats, are experiencing a wide range of climate change-related effects that include increased temperatures, changes in the amount and timing of precipitation (both rain and snow), and increasingly frequent extreme weather events such as record-breaking heat waves or rain and snowfall episodes (Shanley et al. 2015, Foord 2016, Musselman et al. 2018, Peeters et al. 2019). Because mountainous terrain has strong, independent effects on weather and climate (i.e. due to orographic lifting, rain-shadow effects, and others) local- and regional-scale variability can be pronounced, future changes in climate will likely vary accordingly. For example, snow conditions in mountain regions vary substantially at small spatial scales based on local topographic characteristics that influence wind patterns, temperature, and likelihood of rain vs snow (Erickson et al. 2005, Hansen et al. 2019, Peeters et al. 2019).

In areas inhabited by mountain goats, climate change is generally expected to lead to warmer summers and less snowy winters, with an increase in extreme weather events such as heat waves in summer and greater variability in winter snow conditions such as exceptional snowfall events, increased prevalence of rain-on-snow and freeze/thaw cycles, changing patterns of wind driven deposition, and snowpack structure and stability (Shanley et al. 2015, Foord 2016, Musselman et al. 2018, Peitzsch et al. 2021). In moisture-rich, coastal mountain areas, variability may be particularly pronounced because average winter temperatures are often near the freezing point, so small shifts in temperature can produce large, ecologically-significant changes in snowpack, depending upon whether precipitation is deposited as rain or snow (Shanley et al. 2015). In colder, drier interior ranges, changes in winter climate effects may be more incremental, at least in the near-term, because baseline temperatures are further from snow climate “tipping points”. However, sub-freezing winter warming may increase atmospheric water-holding capacity, leading to increased snowfall in such areas (Quante et al. 2021).

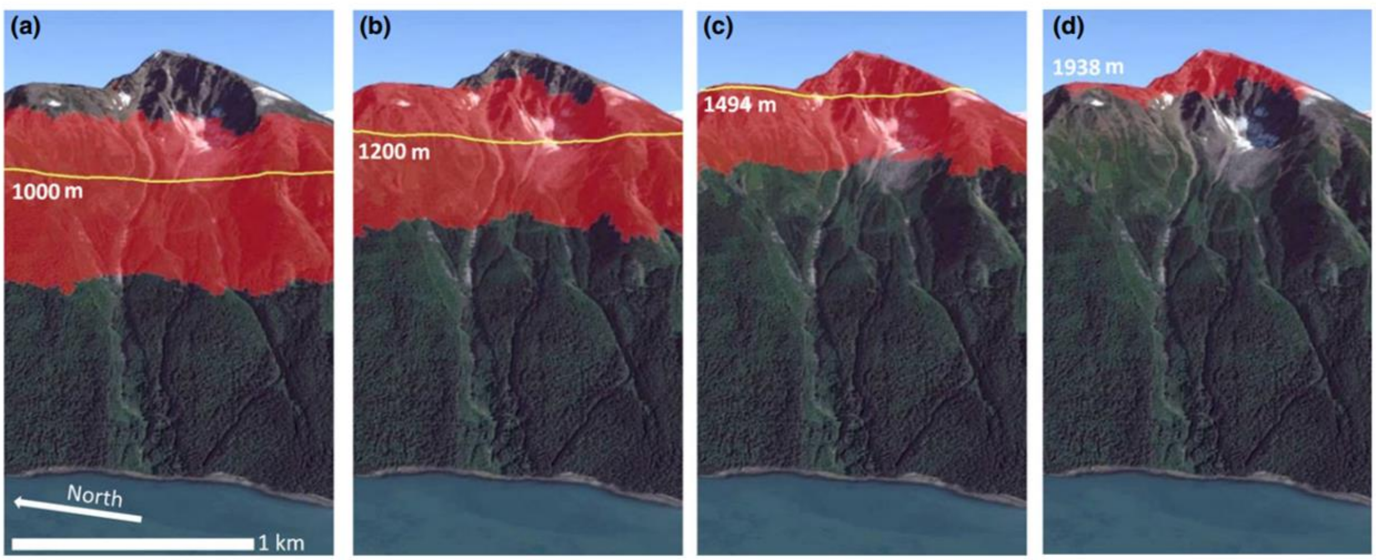
b. Climate-mediated landscape/habitat changes

Iconically referenced as “a beast the color of winter” (Chadwick 1983), mountain goats indeed spend most of the year (October-May) in a landscape dominated by snow and wind; a physical environment that has given rise to specialized morphological adaptations and behavioral and life-history strategies. During winter, snow conditions in mountain goat winter ranges are typically deep (up to 4 m) and mobility restricting, yet during shoulder seasons thin - or in the case of spring - melting snow packs allow more widespread use of the landscape. Beginning in spring (March-May, depending on locality), seasonally-warming temperatures initiate a snow-melting cycle that continues into late summer at the highest elevations, depending on slope and aspect. During this period, snowpack slowly retreats up, and sometimes across, mountainsides as a dynamic and complex mosaic of melting patches, followed by a “green wave” of emergent, highly-nutritious vegetation along the margin of the snow (Fox 1991, Bischof et al. 2012). The rate at which this process occurs influences the relative nutrition and biomass of forage resources available for mountain goats during the summer growing season, with slower, more protracted and spatially-extensive periods of “green-up” being more beneficial for mountain goat growth and productivity as compared to shorter, more contracted, or delayed, green-ups (Pettorelli et al. 2007, Hamel et al. 2009a, 2009b). Snow patches that persist into summer can also act as important resting habitats by allowing goats to cool themselves, especially during the hottest periods (Sarmento et al. 2019).

Climate change-mediated reductions in winter snowpack and increases in summer temperature may influence the quality and availability of forage resources for alpine ungulates (Lenart et al. 2002), as well as the distribution and availability of snow-patch habitats. Warmer spring and summer temperatures may accelerate green-up and reduce the time period during which highly-nutritious, early phenological-stage forages are available. In drier, more marginal areas of the species distribution, warmer temperatures and earlier-melting snow might instead promote drought-like conditions, shorten overall growing seasons, and/or reduce forage resource productivity, quality and availability (Jenkins et al. 2012, Gamon et al. 2013). It may also disrupt the previously predictable spatial pattern of green-up, which could make it more difficult for mountain goats to find optimal vegetation when it is available (as documented in deer; Aikens et al. 2020). Independent of plant phenology dynamics, temperature can also influence baseline forage plant nutritional characteristics. For example, warmer temperatures, leading to faster plant growth and increased lignification of cell walls, result in reduced digestibility of plant tissue and lowered diet quality (Bo and Hjeljord 1991, Weladji et al. 2002). Thus, one effect of warmer summers is an overall decline of forage quality, which, even if small, can have marked effects on animal nutritional condition and productivity (i.e., via multiplier effects [White 1983, McArt et al. 2009]). Overall, relationships between climate change, rates of snowmelt and forage resources are complex, and will likely be most critical under conditions when populations are food limited or near carrying capacity (i.e. marginal habitats, extreme weather years, high population density).

At broader spatial scales and across longer time horizons, changes in distribution and composition of important mountain goat habitats caused by climate change will likely have adverse effects on mountain goat populations. A prehistoric species of mountain goat (*Oreamnos harringtoni*) once existed as far south as Mexico before the last glacial retreat, approximately 11,000 years ago, with their extinction coinciding with a warming planet (Mead and Lawler 1995). Climate change, now accelerated, has resulted in geographically extensive and relatively rapid changes in mountain goat habitat. Increasing temperature in high-elevation habitats has resulted in upward advance of shrub and conifer plant communities, resulting in encroachment and subsequent shrinkage of alpine meadow habitats (Dial et al. 2016). Corresponding upward advancement of alpine plant communities is expected to lag behind thermal suitability due to biogeochemical constraints and slow soil development rates that occur at the highest elevations (Hagedorn et al. 2019), further exacerbating treeline encroachment effects on alpine meadow habitats. Ultimately, due to the conical shape of most western North American mountains, the areal extent of alpine habitat and consequent carrying capacity of mountain goats in native ranges is expected to decline over the long-term (Elsen and Tingley 2015, White et al. 2018; Figure 2). In addition, the loss of important alpine habitat may, in some places, cut off essential corridors for connectivity between habitat patches or mountain goat populations. This may cause further long-term detrimental effects on landscape, genetic, and demographic connectivity among mountain goat populations. For example, Shafer et al. (2012) indicated that local-scale genetic differentiation of mountain goats in coastal Alaska was best predicted by summer habitat connectivity, suggesting that reduction in alpine habitat from forest encroachment is likely to restrict large-scale movement and dispersal. Indeed, extant patterns of mountain goat population genetic structure are strongly influenced by geographical barriers to movement such as deglaciated fiords, icefields, unsuitable low elevation habitats (including forest and non-forest types), and human development (Shafer et al. 2011, Parks et al. 2005, White et al. 2021, Young et al. 2022).

Figure 2. Resource selection function modeling output describing predicted changes in mountain goat summer habitat distribution for four scenarios: (a) current distribution (2005–2015 baseline conditions), (b) year 2085, GCM-GISS-RCP4.5 ("best case scenario"), (c) year 2085, GCM-MRI-RCP8.5/GCM-GFDL-RCP4.5 midpoint ("intermediate scenario), and (d) year 2085, GCM-CCS-RCP-8.5 ("worst case scenario") (from White et al. 2018)



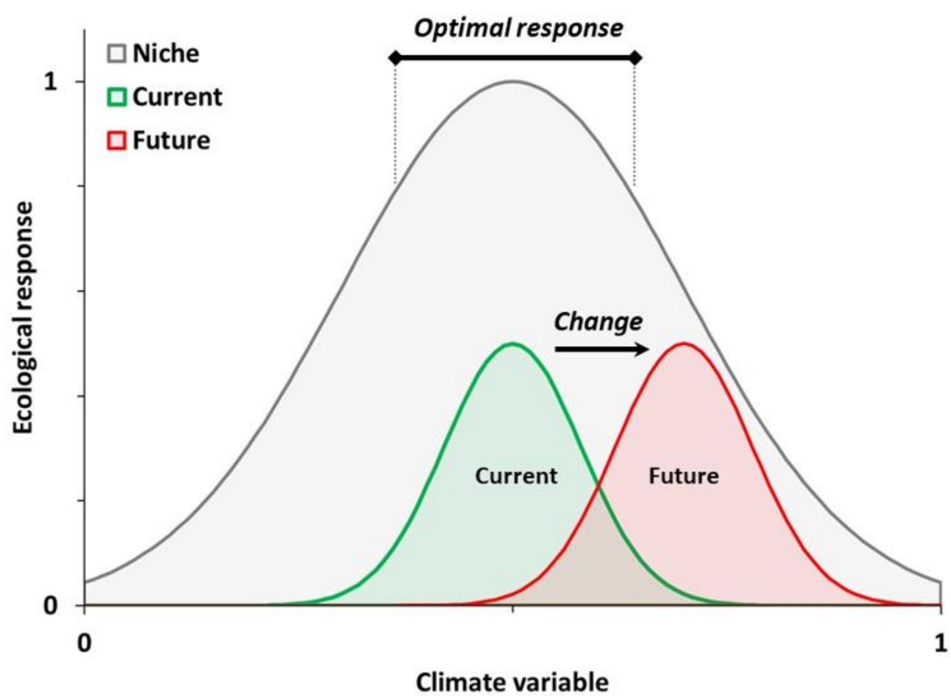
In drier, more interior areas, warming summer temperatures associated with climate change may increase the frequency, intensity and geographic extent of wildfires. Such events can destroy important forested winter range habitats and have detrimental effects on local and regional mountain goat populations. For example, in southwestern British Columbia, mountain goat winter ranges that were highly impacted by fire were 75% less likely to be occupied and contained 80% fewer mountain goats than comparable unburned winter ranges (Nietvelt et al. 2018). Thus, while wildfire is very rare and not a pronounced threat in wet, temperate mountain goat ranges, it can be a significant factor in drier, wildfire-prone parts of their range, especially when winter snow packs are deep and snow intercepting forest canopy has been reduced (Johnson 1983, Nietvelt et al. 2018).

However, less destructive low-intensity wildfires or prescribed burns may, in some circumstances, have beneficial effects in forested winter ranges by maintaining productive understory plant communities (Johnson 1983).

c. Mountain goat responses to variation in weather

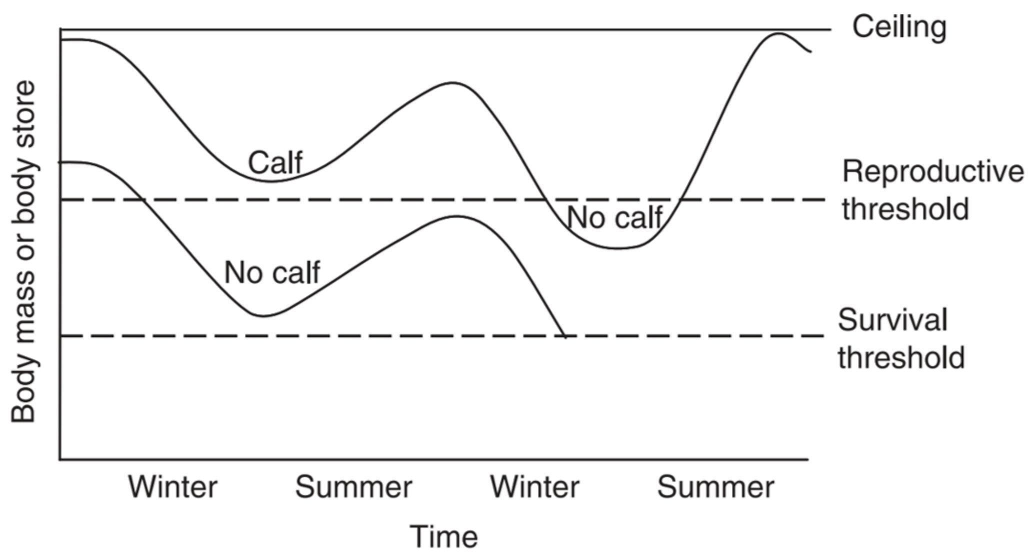
Understanding how climate change affects mountain goat population ecology can be difficult to examine because it requires long-term studies (i.e. climate is generally defined as weather patterns over a 30+ year period). Thus, much of our knowledge about how climate may affect mountain goats is derived from shorter-term studies focused on how variation in weather influences mountain goat behavior and population ecology, including statistically relating individual- and population-level processes to seasonal weather conditions across relatively large geographies. Models derived from quantification of such relationships can ultimately be used to predict how changes may occur across longer time scales to derive inference about expected climate change effects on mountain goat populations across a range of plausible scenarios (*sensu* White et al. 2018, Figure 3).

Figure 3. Conceptual diagram illustrating the ecological niche of mountain goats in relation to variation in climate. The current distribution is characterized as an optimal response to current climate conditions. Due to climate change observed responses may contract and shift towards the extreme of the niche (outside of the optimal zone) which may result in increased stress and reduced performance (adapted from Antão et al. 2022).



Weather and climate are expected to affect mountain goats in a seasonally-integrated fashion (Parker et al. 2009, Figure 4). For example, during the relatively short plant growing season, mountain goats must accumulate substantial body fat and protein reserves (up to 38% increase in body mass; Festa-Bianchet and Côté 2008, T. Stephenson, unpublished data). Such resources are needed to nutritionally carry them through the long winter season; a period when they are in a negative energy balance. Most mountain goat mortalities occur during late-winter or early-spring when animals are most nutritionally stressed, with individuals in better body condition expected to have a higher likelihood of survival (White et al. 2011). Consequently, even though malnutrition-related mortalities most commonly occur in late-winter, deaths can be directly related to the previous summer's thermal and foraging conditions (White et al. 2011).

Figure 4. Conceptual model of the seasonal relationships and lag effects among body mass or body stores, thresholds for survival and reproduction, and calf production by ungulates (from Parker et al. 2009).



Mountain goats, like most northern ungulates, are well-adapted to living in cold environmental conditions, due to the prevalence of such temperatures during most of the year. The principal morphological adaptation to cold temperatures is a long, highly insulative white coat that begins to molt during early-summer; an event that is well-timed for providing heat relief during warm summer days (Déry et al. 2019, Nowak et al. 2020). Molting phenology is sex- and age-specific, and some individuals (particularly parturient females) often retain winter coats into late-summer. Although mountain goats do exhibit the ability to adjust molt timing in response to plant phenology (Déry et al. 2019), imperfectly-timed molting associated with short-term weather variability or extreme events may predispose mountain goats to thermal stress. This dynamic will likely be exacerbated by climate change, especially if increasing weather variability leads to more incidences of temporal mismatch. For domestic ungulate neonates, warmer temperatures in the weeks following birth may reduce physiological stress. However, where weather patterns result in increased frequency of rain and wind events during natal periods, kid mortality caused by hypothermic conditions may result, with obvious negative impacts on population dynamics (Obst and Ellis 1977, Slee 1978).

Independent of molting status, mountain goats exhibit behavioral sensitivity to thermal stress and adopt tactics to minimize effects. For example, in coastal Alaska, mountain goats reduce activity during the warmest parts of the day (Frederick 2015, Michaud 2022), and are also less active during warm, clear days than during cool, rainy days (Fox 1977). Mountain goats also alter habitat selection in response to summer temperature, preferentially using cooler habitats such as snow patches (Fox 1977, Sarmento et al. 2019), or areas adjacent and downslope of glaciers. To escape heat, mountain goats may also shift to cooler, higher-elevation sites in coastal areas (Fox 1977, Frederick 2015, Michaud 2022) or, alternatively, shady lower-elevation subalpine forest habitats in interior areas (Michaud 2022). However, use of such behavioral strategies to mitigate thermal stress may incur nutritional costs or increase predation-risk. Specifically, shifting from nutritionally-productive alpine meadow habitats to more forage-depauperate high-elevation rocky sites is expected to reduce nutritional intake rates, whereas shifting to subalpine forest sites may incur increased risk of predation from stalking predators that rely on concealment cover for successful attacks. Mountain goats rely on escape terrain to reduce risk of predation (Sarmento and Berger 2020), thus leaving the safety of cliffs to access cool microclimates could also lead to an increase in predation.

Temperature can affect growing season conditions and characteristics of forage resources during the critical parturition and summer season. Timing and length of the green-up period can alter availability of high-quality nutritional forages, which in turn affects animal performance, including reproductive success (Côté and Festa-Bianchet 2001, Pettorelli et al. 2007, Hamel et al. 2009a, 2009b). Because lactation is energetically costly, timing parturition to optimally coincide with availability of emergent, early phenological-stage forage resources is important to enhance nutritional condition and hence, to provision offspring. Climate change is likely to result in greater variability in green-up timing with an underlying shift toward earlier and, possibly, more abbreviated duration. If mountain goats are unable to adjust parturition timing to accommodate such changes, a temporal mismatch may occur that can have negative effects on reproductive performance [as documented for caribou (*Rangifer tarandus groenlandicus*) in the arctic; Post and Forchhammer 2008]. However, even if mountain goats are able to adapt and adjust parturition timing to gradually shifting patterns in green up, predicted increase in short-term variability in summer weather and extreme events are less “adaptable” and likely to result in persistent instability.

In sum, behavioral trade-offs and alteration of summer forage nutritional dynamics associated with increasing summer temperature is likely to have negative consequences for mountain goats from both a nutritional and demographic perspective. Indeed, long-term research conducted in multiple study areas across coastal Alaska indicated that increasing summer temperature resulted in reduced mountain goat annual survival (White et al. 2011), and is expected to translate into long-term reductions in population growth under a range of different climate change scenarios at a representative site within that region (White et al. 2018). Nonetheless, further understanding of spatial variability in such outcomes is needed, especially in light of observed differences in summer temperature behavioral responses between coastal and interior ecotypes (i.e. Michaud 2022).

Winter snow depth plays an important role in regulating the nutritional and energetic budget of mountain goats. Snow not only buries and reduces availability of important winter forages (Fox 1983, White et al. 2009), it also increases energetic costs of locomotion and restricts movement (Dailey and Hobbs 1989, Poole et al. 2009, Richard et al. 2014, Shakeri et al. 2021). As a result, both adult and kid survival decline in winters with high snowfall (Hamel et al. 2010, White et al. 2011, Théorêt-Gosselin et al. 2015). Thus, taken in isolation, projected declines in snowfall from climate change are likely to benefit mountain goat populations. However, benefits of reduced snowfall may be counterbalanced by other effects of climate change. For example, demographic modeling simulations across a range of different climate change scenarios suggest that beneficial effects of reduced snowfall are likely to be outweighed by negative effects of increasing summer temperature (White et al. 2018). This occurs because the rate-of-change and effects of summer temperature will likely be greater than the corresponding effects of reduced winter snowfall (i.e. over time, snowfall effects on energetics and nutritional physiology diminish and eventually become negligible).

Even though total snowfall is a strong predictor of mountain goat survival, it does not explain all the variation in overwinter mortality. For example, avalanches constitute an important source of mountain goat mortality, comprising 30-60% of all mortalities in coastal Alaska (White 2022). Although total snowfall may be a determinant of avalanche prevalence, other factors such as rain-on-snow events or persistent weak snow layers may also be important drivers of snowpack instability (Peitzsch et al. 2021). The latter factors are more complex to predict but are likely to be more prevalent with predicted warming winter temperatures, especially in coastal regions that are already near the freezing isotherm, or snow vs rain “tipping point”. Alternatively, delayed or reduced accumulation of snow in high-elevation areas during autumn may extend the period during which forage is readily accessible. Lengthening of a snow-free autumn season may benefit males during the breeding season; a period when males rapidly diminish nutritional stores necessary for overwinter survival (i.e.

Pelletier et al. 2008). Yet, it is important to acknowledge that shoulder season forage has lower nutritional quality than summer, and the primary benefit likely relates to reduced energetic expenditures needed to consume forage, in contrast to when they are buried under snow.

d. Health

Weather and climate may directly and indirectly affect the health and productivity of mountain goats by influencing nutritional ecology and physiological stress levels, as well as altering host-parasite dynamics, and enabling establishment of novel pathogens and parasites. As a species adapted to a cooler climate in the majority of their range, warming climates may result in mountain goats and sympatric species experiencing an expanding distribution and abundance of thermally-restricted infectious agents and parasites otherwise rare in the cold conditions typical of mountainous habitats (i.e. Aleuy et al. 2018, Cohen et al. 2020). As compared to other northern ungulates, current evidence suggests that mountain goats have relatively limited exposure to many infectious diseases present in other mountain ungulates such as wild sheep (bighorns and thinhorns), at least in the northwestern portion of the range (Lowrey et al. 2018, White 2022, B. Jex and H. Schwantje, BC Ministry of Forests, unpublished data). As a consequence, naïve populations that have not been previously exposed or co-evolved with distributionally expanding diseases and parasites may be especially vulnerable to climate change linked disease effects, following the novel pathogen hypothesis (Alford 2001).

As discussed in previous sections, climate change could affect the availability and quality of summer forage and alter foraging dynamics, as well as influence winter severity and snow conditions, which in turn, can negatively impact individual body fat and protein reserves. Poor body condition may lead to individuals being predisposed to, and deleteriously affected by, secondary factors such as predator (including humans; Frid and Dill 2002) disturbance (i.e. endocrine stress response effects on reproduction; Dulude-de Broin 2020), insect harassment, and, importantly, pathogen and parasite exposure. Poor body condition and subsequent physiological stress responses can also decrease neonate survival (Douhard et al. 2018) and reproductive rates through reduced conception rates, maintenance of pregnancies and maternal care of neonates (Barboza and Parker 2008, Montieth et al. 2013, Stephenson et al. 2020). In addition, the innate and acquired immune system responses of animals can be affected, putting them at a higher risk of acquiring endemic or novel infections (Acevedo-Whitehouse and Duffus 2009, Hing et al. 2016). These infections, in turn, can compromise digestive system function, leading to further nutritional stress, and ultimately, negative impacts to reproduction and survival (Acevedo-Whitehouse and Duffus 2009). Sustained physiological stress caused by longer-term environmental stressors and poor body condition can also cause increases in shedding of infectious agents, and severity of clinical symptoms which can lead to higher rates of disease prevalence and morbidity, and potentially shift formerly stable host-parasite equilibriums to become more pathogenetic (Hing et al. 2016)

Predicting the contribution of environmental stressors to the immunity and infection rate of mountain goats is complex, as effects can interact or have additive costs, and manifest at multiple levels (Acevedo-Whitehouse and Duffus 2009). Further, the timing and duration of the stressor, as well as physiological differences across individuals, can also determine whether a stressor will result in enhancement or suppression of the immune system, making generalities about stress-immunity linkages in wildlife difficult (Martin 2009). However, recently developed gene-based techniques may be utilized to improve our understanding of disease susceptibility in wildlife. For example, through measuring changes in levels of immunity-linked gene-transcripts it can be possible to detect an early warning of potentially compromised health and at the same time, impact of environmental stressors such as those caused by climate change, on individuals and populations (Bowen et al. 2020, 2022). Applying these techniques to mountain goats as a part of baseline monitoring could provide compelling evidence of the impacts of climate change to population health, and increase our understanding of disease dynamics (Bowen at el. 2020, 2022).

e. Interspecific Interactions

Human modification of landscapes combined with climate variability can have profound impacts on interspecific relationships and community ecology of large mammals in western North America (Serrouya et al. 2021). In British Columbia, large-scale logging has increased abundance of moose (*Alces alces*) and subsequently wolves to the detriment of spatially-widespread but locally rare caribou populations. Such instances of apparent competition, where an abundant prey species numerically subsidize generalist predators and result in disproportionately negative impacts on rare, secondary prey species, can also apply to mountain ungulates such as Dall's sheep (*Ovis dalli*; Arthur and Prugh 2010), Sierra Nevada bighorn sheep (*Ovis canadensis sierrae;* Johnson et al. 2013) and presumably mountain goats. Such relationships may be accentuated when climate conditions exert strong effects on the population ecology of predators, such as wolves (*Canis lupus*; Mahoney et al. 2020), or promote the natural colonization of novel predators such as cougars (*Felis concolor*) into new areas. Mountain goat health may also be indirectly affected by climate change through large mammal predator-prey apparent-competition pathways, if species such as moose, elk and deer continue to increase in abundance or naturally expand their range into mountain goat habitat in previously-unoccupied areas and promote the spread of pathogens and parasites. Changes in weather and climate may also influence interspecific interactions among sympatric mountain ungulates, such as mountain goats and bighorn sheep, especially when critical resources are limited (Berger et al. 2022). While such dynamics may be complex and difficult to forecast, the increased sympatry, and potential disease transmission, with newly-colonizing ungulates may be partially offset by negative demographic effects of increased predation pressure; a relation that may reduce local mountain goat density and intra-specific disease transmission.

3. Management implications and mitigation

Over the long-term, climate change is predicted to alter mountain ecosystems and, in turn, affect mountain goat populations. In many ecological contexts, we expect these effects to be deleterious for mountain goats [but see Gude et al. (2022) regarding introduced populations]. Our understanding of these complex dynamics is incomplete, and we expect that effects related to climate change will be spatially- and temporally-variable. We find this uncertainty all the more reason to be proactive, and to identify potential implications and associated management tools that can be implemented to mitigate projected effects.

Projected changes in climate are likely to have short- and long-term effects on timing of key biological events such as breeding, parturition, altitudinal migration, and seasonal use of habitats and distribution. In addition, changes in plant phenology, summer growing-season length and winter severity and length are likely to result in changes to population productivity, and ultimately, abundance. Collectively, such changes may result in shifts in geographic distribution and habitat selection patterns that may require revising delineation and protection of important, or critical, habitats from resource extraction and development activities. Also, adjusting timing windows during which such habitats need to be especially protected from any disturbance is also important. For example, if parturition dates or winter-range residency periods shift in response to climate change, then timing windows currently used in management contexts may need to be adjusted accordingly. Distributional shifts may also involve crossing jurisdictional boundaries resulting in changing management and conservation implications and responsibilities (John and Post 2022).

If mountain goat populations decline or become more variable in response to long-term trends or greater stochasticity in shorter-term weather patterns, harvest managers may need to anticipate changing hunting season timing and bag limits accordingly. Mountain goat hunting is already not sustainable and curtailed in some parts of their range (due to a variety of causes), and it is likely to be an increasingly common situation elsewhere given the additive effects of climate change. Ultimately, climate change may result in increased sensitivity to existing impacts and reduced resilience, leading to more conservative management. Overall, long-term capability of habitats to support mountain goats is likely to decline with continued climate change. Combined with generally weak population-level responses to density (Turgeon 2022), the frequency with which populations display positive growth is likely to decline. As such, sustainable harvest, as a proportion of standing population is likely to be reduced. Ultimately, such effects may require reconsideration of appropriate land management uses in mountain environments, including consumptive harvest practices and management of direct and indirect human disturbance (*sensu* Northern Wild Sheep and Goat Council 2020).

Mitigation of climate change effects are challenging but may occur at small and large scales. At global or national scales, policies focused on minimizing human contributions to climate change are likely to be beneficial to mountain goats. At local scales, strategic efforts to minimize impacts to mountain goat populations and their habitats will help improve resilience and buffer negative effects of climate change. For example, protection of important habitats from industrial impacts (i.e. logging, mining, commercial activities) and excessive human disturbance will be increasingly important. Mitigation of high intensity wildfires may aid in retaining integrity of winter range habitats in relatively dry, wildfire-prone areas, such as southwestern British Columbia (Nietvelt et al. 2018).

Strategies considered by management agencies to buttress vulnerable or declining populations also include mountain goat introduction into suitable habitats outside of their historic range, augmentation (where populations are small but extant and threats can be mitigated), and reintroduction (where native populations have become extirpated). The first strategy has a long history with mountain goats (Hurley and Clark 2006), with many introduced populations growing faster than the sources from which they came (DeCesare and Smith 2018). However, managers should consider possible unintended consequences of artificial introduction, including impacts to naïve vegetation (Houston et al. 1994, Happe et al. 2022), competition with native ungulates (Flesch et al. 2016), and increased opportunity for disease transmission (Wolff et al. 2014, 2016). Augmentation and reintroduction are free from these concerns if one assumes that native flora and fauna possess necessary adaptations to the presence of goats. But mountain goats translocated to native habitats can be expected to suffer high mortality (Myatt et al. 2010), and surviving animals are likely to establish themselves in areas other than those intended (Harris et al. 2021). Overall, success of reintroduction programs into native habitats has been less than 50% (Harris and Steele 2015) and if not implemented appropriately may even lead to deleterious effects on extant populations in augmentation scenarios (Turgeon 2022). Under any of these three strategies, translocated mountain goats are likely susceptible to the same climate-related stresses as residents.

4. Information needs and research gaps

Mountain goats exhibit an array of specialized adaptions necessary for inhabiting and surviving in extreme physical environments. Although such characteristics invoke deep cultural fascination and appreciation, they also illuminate the narrow margin for which the species contends for survival in such environments. Mountain goats can be viewed as a sentinel of change in mountain ecosystems, due to the sensitivity with which small changes at the margin of existence can translate into large effects. Yet, to fully understand the dynamics of how mountain goats are influenced by weather and climate change, much work remains to be done at smaller-scales that utilize mechanistic frameworks as well as at larger scales to document broader species-wide patterns. Such work is critical for understanding and projecting how mountain goat populations may be affected at management and conservation-relevant scales. Key information needs and research gaps are identified in Appendix 1.

5. Monitoring considerations and recommendations

Effective conservation of mountain goats requires clear articulation of short- and long-term management and conservation objectives by stakeholders. At a broad scale, objectives often focus on ensuring sustainability of populations, and are most effective when designed, implemented and evaluated using systematic decision-making processes that incorporate uncertainty and associated risk (Gude et al. 2022). To a certain degree, uncertainty and risk can be mitigated by improved understanding of study systems but not fully ameliorated, especially when projecting into the future. In this context, climate change represents an increasingly important factor that will likely require not only clear definition of conservation objectives, but also routine reassessment going into the future to ensure such impacts are appropriately accounted for. Such assessment is ideally conducted using a decision-analytic framework that integrates scientific knowledge related to climate change along with other scientific knowledge in a comprehensive fashion (Martin et al. 2011, Gude et al. 2022). A decision-analytic framework provides clear roles for increased monitoring and targeted research to assess current conditions and achievement of objectives, thereby justifying increased attention and funding for the necessary monitoring and research programs.

Mountain goats are among the least studied and monitored large mammals in North America. Given increasing conservation challenges associated with climate change, and other issues, it is important to expand the spatial extent and temporal frequency of monitoring, in general. Thus, a critical primary recommendation relates to prioritizing funding for mountain goat monitoring to ensure that status and changes in local and regional populations can be rigorously documented and provide the basis for development of appropriate conservation and management strategies. Specifically, long-term, intensive monitoring across a representative array of sites is critical for relating climate conditions to demographic responses.

Monitoring mountain goat populations in the context of climate change is likely to present new challenges that may require innovation of field and analytical methodologies including study design, sampling, analysis (*sensu*

Gude et al. 2022) as well as use of indigenous knowledge and hunter harvest data in integrative frameworks (*sensu* Jessen et al. 2022). Traditional methods for monitoring mountain goats across broad landscapes involving sightability model-linked aerial surveys (Poole et al. 2007, Rice et al. 2009) may need to be adjusted or re-calibrated, especially if increasing summer temperatures result in increased use of forested subalpine habitats (Michaud 2022). Mark-resight aerial or ground-based survey methods (including observational or genetic techniques; Festa-Bianchet and Côté 2008, Poole et al. 2011, McDevitt et al. 2021) may circumvent challenges by providing real-time sighting probability estimates, but can be costly or applicable only at relatively small spatial scales.

Optimal timing of mountain goat population surveys, which ideally coincide with seasonal time windows when animals are in the most visible habitats, are likely to shift as climate change alters distributional and behavioral patterns. Re-examining and adjusting population monitoring methods to account for such projected changes, even among years within the same area, will be important for ensuring estimates of population size and composition are accurate, precise, and reliable across time (i.e. represent true changes in population dynamics and not changes in survey or other conditions). Appropriate methods may be dependent on local conditions (i.e accessibility, study area size, weather dynamics). It is also important that changes in monitoring be preceded by methodological cross-walk analyses to ensure that long-term monitoring data sets can be seamlessly integrated irrespective of the monitoring method used.

Re-assessment of drivers of population dynamics and associated ecological covariates may also represent important monitoring considerations. Specifically, if climate change is increasing in importance as a population-driver, more emphasis may need to be placed on characterizing weather conditions and finer spatial- and temporal- scales than previously used. Fortunately, satellite-based remote sensing climate data has become increasingly available across a comprehensive array of spatial- and temporal-scales, and may be well suited for monitoring short-term weather and long-term climate changes for local and regional population trend analyses. However, spatial resolution of climate data products may still have limitations for most smaller-scale analyses, and implementation of local-scale monitoring programs may be critical for understanding individual- or subpopulation-level responses. Accessibility and affordability of weather-monitoring devices can play an important role in this domain and include the use of trail and timelapse cameras, highly-portable environmental sensors (e.g. iButtons) and animal-borne GPS radio-collar temperature sensors. Such devices can allow for increased site-specific spatiotemporal monitoring of environmental conditions in mountain goat range. In addition to weather and climate data collection, standardized characterization of plant phenology, forage quality and availability, snow ablation patterns as well as winter snowpack characteristics (i.e. rain-on-snow events, persistent weak layers) are likely to be increasingly important covariates for monitoring. Longer-time horizon monitoring such as changes in shrubline/treeline, habitat composition and distribution also represent important considerations, but may not need to be monitored at annual time intervals, or as frequently, as other metrics. At broader spatial scales, regional- or range-wide data collection and analyses will be particularly important for understanding population responses across the full continuum of species-wide conditions.

The distribution and prevalence of infectious diseases and parasites that may potentially influence mountain goats are expected to be at least partially climate sensitive. Broad-based herd health assessments should be integrated into monitoring programs whenever possible. While mountain goat herds may be remote, and live captures challenging, there are new models of wild ungulate herd health assessments that are proving useful and may also be applied to this species. A variety of practical and remote methods have been summarized and include: verbal descriptions and local knowledge interviews, photographs, physical inspection, measurement and sampling of harvested animals, animals opportunistically found dead and individuals handled during live-capture operations. All are opportunities to better understand health even if samples are archived. Standardized protocols have been developed for this purpose for wild sheep (WAFWA Wildlife Health Committee 2015) and can be easily modified for mountain goats. Sampling methods vary from field collection of fecal pellets, detailed necropsies, to collection of swabs, blood, fecal, hair, and tissue samples from live animals. All should be collected, submitted, and analyzed following a standardized protocol.

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Appendix 1. Information needs and research gaps

Mountain goats exhibit an array of specialized adaptions necessary for inhabiting and surviving in extreme physical environments. Although such characteristics invoke deep cultural fascination and appreciation, they also illuminate the narrow margin for which the species contends for survival in such environments. Mountain goats can be viewed as a sentinel of change in mountain ecosystems, due to the sensitivity with which small changes at the margin of existence can translate into large effects. Yet, to fully understand the dynamics of how mountain goats are influenced by weather and climate change, much work remains to be done at smaller-scales that utilize mechanistic frameworks. Such work is critical for understanding and projecting how mountain goat populations may be affected at management and conservation scales. Key information needs and research gaps are identified in the table below.

Subject	Key information needs and research gaps:
Weather and climate	•Acquisition of finer resolution weather and climate data at the individual mountain goat and population-level scales. •Improved capability to characterize the frequency and spatial extent of rain-on-snow events, and to better understand and characterize how weather events influence snow-pack stability and avalanche risk.
Habitat ecology	•Assess the efficacy of prescribed burning or mechanical removal of tree encroachment into alpine areas to maintain or improve goat habitat, or mitigate frequency of high intensity fires on forested winter range in arid areas. •Characterize the role of water availability as a driver of mountain goat presence, recognizing water availability could be reduced from climate change. Also, how does soil water availability influence secondary plant compound concentration and other aspects of forage palatability and nutritional quality. •Understand temperature and hydric effects of vegetation growth and palatability, plant phenology and physiology in contexts directly relevant to mountain goat nutritional ecology (including micro- and macro-nutrient needs).
Physiology and health	•Assess disease/parasite distribution, timing, prevalence, impacts on mountain goat health (including pathogens and impacts of increases of biting flies in the alpine) and associated projected changes in risk. •How does increase environmental stress associated with climate change impact individual and herd health and immunity/resistance to disease and/or parasites? •Detailed understanding of thermal stress physiology, thresholds and behavioral responses.
Population ecology and behavior	•Improved mechanistic understanding of weather and climate effects on mountain goat behavior and population ecology including growth, reproduction, adult and neonate survival. •Improved understanding of the importance of avalanches as a cause of climate-linked mortality, and also whether avalanche habitats are beneficial and preferentially used during non-winter months. •Comprehensive understanding of how effects vary spatially and determination of regions/populations that are "winners vs losers" from climate change. •Acquire a detailed understanding of weather and climate interactions with predation risk from apparent competition and the effects of range expansions of novel predators (e.g., cougar), including impacts of exploitative and interference competition and also how mismatched white camouflage in landscapes lacking snow influences predation-risk. •Increased efforts to conduct comparative and standardized studies across diverse geographies to improve understanding of spatial and ecotypic variability.
Management	•Assessment of how shifting distributions of goats with climate change might influence management boundaries. Goats are often managed (i.e. harvest quotas) at small spatial scales (population/herd level) and a few groups moving from a lower to higher elevation mountain complex could cause a decline or extirpation in a management area (and an increase in an adjacent area).

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An Empirically Grounded Framework For Tuning a General Bighorn Sheep Space Use Model to Specific Environmental Contexts

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ABSTRACT: Accurately predicting bighorn sheep movements is imperative for efficiently mitigating pathogen transmission risk, both within and between hosts. As habitat specialists, most bighorns share core attributes of space use, including affinity for cliffy terrain, aversion to dense forest, preferences for expansive viewsheds, and proximity to water. Yet the relative importance of these factors, at the both the individual and the herd level, varies with necessity and availability. For example, selection for slope shows strong seasonality in Rocky Mountain bighorn ewes, whose synchronous birth pulse leads to synchronous slope requirements, but this pattern does not emerge under the diffuse birth pulse of desert bighorn ewes. On the other hand, distance to water is a salient driver of space use in water-limited environments, but is much less important in environments where water is not scarce. Here, our objective is to outline a conceptual framework for understanding bighorn space use across latitudes, and then confront the framework with empirical data. We achieve this methodologically by fitting and comparing seasonal habitat selection coefficients associated with four key habitat attributes — slope, ruggedness, percent cover, and distance to water — for bighorns across a range of environmental contexts. Our findings illustrate that while these same core factors are good predictors of bighorn space use across a wide variety of environments, their relative importance may be recalibrated depending on the local context. Clear *a priori* expectations about which factors should be most important when may provide managers a means of tailoring bighorn space use predictions to better match particular landscapes, potentially improving pathogen transmission risk assessments for herds where local movement data are limited.

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KEY WORDS: bighorn sheep, pathogen transmission risk, seasonal habitat selection.

Estimating the Fission-Fusion Dynamics in Social Behavior of Bighorn Sheep

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ABSTRACT: Understanding and predicting movement of bighorn sheep is critical for conservation planning and disease risk mitigation, and important environmental drivers of bighorn movement have received extensive attention. However, social factors surrounding group fission and fusion events also directly affect movement, but they are infrequently measured in the wild and rarely linked to underlying factors such as relatedness or shared life stage. Here, we explore three dimensions of bighorn fission-fusion dynamics: group size, composition, and spatial cohesion. Identifying the critical processes that shape female social structure and fission-fusion dynamics is an important step toward accurately forecasting how animals interact with ramifications on connectivity, gene flow, and pathogen transmission. We estimate these fission-fusion dimensions and link fission-fusion events to social processes and fitness outcomes using a long-term, individual-level dataset on bighorn sheep from the Bison Range in Montana. We examine the variance in group composition, group size, and group spatial cohesion and assess what part of those variances can be systematically explained by population size, age, or sex structure. We model group switching choices as a function of social covariates through a discrete choice model contrasting conditions such as relatedness, cohort representation, agreement in reproductive status, and group size in an animal's current group to parallel conditions in all other groups detected that day. This preliminary investigation of core fission-fusion attributes, along with their motivating biological processes, is a first step toward quantifying the role of social forces in shaping bighorn movements. Integrating these factors with environmental information may improve our ability to forecast movements and predict the consequences of connectivity on system dynamics.

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KEY WORDS: bighorn sheep, connectivity, gene flow, group dynamics, movement, pathogen transmission.

Seasonal Variation in Connectivity Behavior of Bighorn Sheep

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ABSTRACT: Connectivity between bighorn sheep (*Ovis canadensis*) herds is important for the spread of *Mycoplasma ovipneumoniae.* We modeled seasonal variation in connectivity between herds using GPS location data from rams across the state of Nevada. First, we used a hidden Markov model to decompose the GPS trajectories into home-ranging and foraying behavioral states based on the characteristics of the movement trajectories. We then used step selection functions fit to the foraying trajectories to model seasonal habitat suitability based on slope, ruggedness, distance to water, and vegetation type. Finally, we predicted seasonal connectivity among herds using Circuitscape, which represents the landscape as an electrical circuit with varying levels of resistance to the flow of current between nodes dependent on the local habitat. To assess seasonal changes in the connectivity of the landscape, we created spatially explicit metapopulation models using season-specific connectivity values in the dispersal function and measured changes in system-wide connectivity.

Biennial Symposium of the Northern Wild Sheep and Goat Council 23:3; 2022

KEY WORDS: bighorn sheep, connectivity, foray behavior, *Mycoplasma ovipneumoniae*, pathogen transmission risk, seasonal habitat suitability.

Why Do Some Female Bighorn Sheep Go On Breeding Migrations, While Others Stay in Their Local Wintering Range? Inbreeding Avoidance, Tradition, and Social Transmission

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ABSTRACT: Seasonal migrations are common for many ungulate species, either to find resources, for birthing or to find mates. While breeding migrations are a means for males to find receptive females, and females migrate to lambing areas in the spring, it is less obvious why some female Rocky Mountain bighorn sheep (*Ovis canadensis*) in the Sheep River (SR) population spend rut on their natal winter range where they are likely to mate with rams also natal to the SR population, while others migrate to distant areas of alpine habitat where they are more likely to encounter rams from neighboring populations. The purpose of this study was to determine the proximate and ultimate causes of female breeding migrations in bighorn sheep and to compare these to resident females in a population of bighorn sheep in Sheep River Provincial Park, Alberta, Canada. We hypothesized that individual migratory tendency (i.e., resident or migrant) is 1) socially transmitted from mother to daughter or 2) is consistent within an individual, and/or 3) migration functions as an inbreeding avoidance mechanism. To test these hypotheses, we examined the association between the migratory tendency of mothers and subsequent migratory tendency of daughters once they were adults. We then compared the mean relatedness of resident and migrant females to the dominant males at Sheep River for each rutting season, between 2006 and 2021. The migratory tendency of daughters was not associated with the migratory tendency of mothers. Furthermore, individual migratory status was not fixed or consistent across years. We found no significant difference in the mean relatedness of resident and migrant females to the dominant males at Sheep River, and thus rejected the idea that females might migrate to avoid breeding with closely related males. To evaluate alternative ideas on why females might migrate to breed elsewhere, we are currently extending the analysis to include 1987-2001 when we collected comparable data on female fidelity to natal winter range during rut.

Biennial Symposium of the Northern Wild Sheep and Goat Council 23:4; 2022

KEY WORDS: Alberta, bighorn sheep, breeding migration, migrants, residents, seasonal migrations.

Seeing is be-Leaving: Perception Informs Migratory Decisions in Sierra Nevada Bighorn Sheep (*Ovis canadensis sierrae*)

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ABSTRACT: Seasonal migration is a behavioral response to predictable variation in environmental resources, risks, and conditions. In behaviorally plastic migrants, migration is a conditional strategy that depends, in part, on an individual's informational state. The cognitive processes that underlie how facultative migrants understand and respond to their environment are not well understood. We compared perception of the present environment to memory and omniscience as competing cognitive mechanisms driving altitudinal migratory decisions in an endangered ungulate, the Sierra Nevada bighorn sheep (*Ovis canadensis sierrae*) using 1,298 animal years of data, encompassing 460 unique individuals. We built a suite of statistical models to partition variation in fall migratory status explained by cognitive predictors, while controlling for non-cognitive drivers. To approximate attribute memory, we included lagged attributes of the range an individual experienced in the previous year. We quantified perception by limiting an individual's knowledge of migratory range to the area and attributes visible from its summer range, prior to migrating. Our results show that perception, in addition to the migratory propensity of an individual's social group, and an individual's migratory history, are the best predictors of migration in our system. Our findings suggest that short-distance altitudinal migration is, in part, a response to an individual's perception of conditions on alterative winter range. In long-distance partial migrants, exploration of migratory decision-making has been limited, but it is unlikely that migratory decisions would be based on sensory cues from a remote target range. Differing cognitive mechanisms underpinning short and long-distance migratory decisions will result in differing levels of behavioral plasticity in response to global climate change and anthropogenic disturbance, with important implications for management and conservation of migratory species.

Biennial Symposium of the Northern Wild Sheep and Goat Council 23:5; 2022

KEY WORDS: seasonal migration**,** Sierra Nevada bighorn sheep.

Landscape Features Outperform Habitat to Explain Genetic Connectivity of Bighorn Sheep in Waterton-Glacier International Peace Park

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ABSTRACT: We evaluated bighorn sheep (*Ovis canadensis*) telemetry data and genetic samples collected in Glacier National Park, Waterton Lakes National Park, and the Blackfeet Reservation to estimate the influence of landscape features on bighorn sheep genetic connectivity. Over 168,400 GPS locations were collected between 2002 and 2011 for 97 bighorn sheep, and we generated genomic data for 95 individuals using the High-Density Ovine array. Using a machine-learning optimization approach, we conducted a landscape genetic analysis of genomic kinship between all pairs of individuals with GPS locations during the rut (November through December). We determined rut locations were more informative than capture locations for landscape genetic analysis, likely because capture locations varied by time of year and may not accurately represent an individual's location during genetic exchange. We evaluated a local resource selection model to represent habitat and a suite of possible landscape characteristics predicted to influence genetic connectivity, including water bodies, tree cover, shrub cover, and other surface characteristics, such as slope and distance to steep terrain. We found that water bodies and tree cover were the most important predictors of resistance to genetic connectivity in the study area. We applied this information to predict how genetic connectivity of bighorn sheep may be influenced by current and future changes to the landscape, such as tree cover reduction due to wildfire. Our results provide insights regarding the spatial scale and landscape influences of gene flow in a native bighorn sheep population with no history of translocations. This information can be used to determine if certain habitat characteristics can be managed to facilitate or impede long-term connectivity among bighorn sheep populations and determine if genetic connectivity of bighorn sheep may be affected by climate change.

Biennial Symposium of the Northern Wild Sheep and Goat Council 23:6; 2022

KEY WORDS: bighorn sheep, genetic connectivity, Waterton-Glacier International Peace Park.

Range-Wide Genetic Analyses to Guide the Future Management of California Bighorn Sheep

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ABSTRACT: Over the past century, bighorn sheep managers have conducted hundreds of translocations across western North America to augment existing populations and to reintroduce individuals to previously occupied habitats. While these translocations have been broadly successful in restoring populations, most were undertaken without baseline genetic information. For example, the taxonomic basis of the putative California bighorn sheep lineage has been historically contentious, resulting in jurisdictions differing in whether they manage California and Rocky Mountain bighorn sheep as the same entity or separate evolutionarily significant units. This distinction is important for future management because all California bighorn herds in the United States descend from repeated translocations of individuals sourced from a few herds in British Columbia, potentially resulting in low levels of genetic diversity and limited evolutionary potential. In fact, some jurisdictions have already mixed California and Rocky Mountain individuals to mitigate the potential negative consequences of low diversity in California bighorn herds. To guide future management, we genotyped >2,000 bighorn sheep individuals from across western North America using DNA sequence data. Based on genomewide variation at several thousand single nucleotide polymorphisms (SNPs), we uncovered strong genetic differentiation between California, Desert, and Rocky Mountain bighorn sheep, suggesting they indeed represent independent evolutionary lineages. Further, we identified several herds with mixed ancestry, resulting from past translocations and occasionally subsequent dispersal. Finally, while California bighorn sheep generally have low levels of genetic diversity, there was ample variation, so those California herds with higher diversity could be prioritized as sources for future translocations. Based on patterns of differentiation, hybridization, and levels of genetic diversity, we conclude by proposing several suggestions for the future management of California bighorn sheep.

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KEY WORDS: California bighorn sheep, desert bighorn sheep, genetics, Rocky Mountain bighorn sheep.

With Great Powder Comes Great Responsibility: Assessing the Response of Sierra Nevada Bighorn Sheep *(Ovis canadensis sierrae)* to Backcountry Skiing

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ABSTRACT: The influence of humans on wildlife is most notable through habitat loss and fragmentation. The mere presence of humans, however, can trigger antipredator behaviors, alter space use, and limit access to resources. Growth in outdoor recreation has increased the presence humans in natural areas creating potential conflict. To assess the effect of recreation on the habitat use of Sierra Nevada bighorn sheep (*Ovis canadensis sierrae*), we evaluated the selection of home ranges and selection of features within home ranges in relation to backcountry skiing. Sierra bighorn avoided areas with backcountry skiing when selecting home ranges ($\beta = -0.06$, $p < 0.05$) and locations within those ranges ($\beta = -0.18$, $p < 0.05$). At both scales, however, sheep avoided ($\beta = -0.86$, $p < 0.05$) or showed indifference to ($\beta = -0.05$, $p = 0.18$), distance to backcountry skiing potentially indicating a lack of alternative sites or a response that is complicated by terrain. We add to a growing body of literature which shows wildlife can be sensitive to forms of human activity that have been perceived as having minimal impact. Furthermore, we highlight the need to incorporate responses to recreation in management planning to ensure the sustainability of wildlife populations as recreation increases globally.

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KEYWORDS: *Ovis canadensis sierrae*, Sierra Nevada bighorn sheep, Strava, backcountry skiing, habitat selection, recreation.

Evaluating non-traditional approaches to monitor a small and remote Rocky Mountain bighorn sheep *(Ovis canadensis canadensis)* population

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ABSTRACT: Monitoring demographics of small wildlife populations is often challenging but is especially important given that relatively small declines in abundance can greatly increase small populations' risk of extirpation. Advances in statistics and molecular tools have expanded the suite of techniques that wildlife managers can use to monitor populations. Teton Range bighorn sheep are low in abundance and challenging to monitor using traditional approaches, in large part due to their diffuse, year-round occupation of the range's higher elevations. We are evaluating the utility of using a non-invasive genetics approach to monitoring by systematically collecting fecal samples at mineral licks and high-use areas during the summer, identifying individuals from DNA on samples, and fitting the resulting data into a capture-recapture framework to estimate abundance, survival, and recruitment. We used GPS-collar data from 28 adult female bighorn sheep monitored 2008-2010 to select a set of previously identified mineral licks that all 28 animals visited at least once during summer months (June-September). We collected fecal samples from these sites at approximately two-week intervals or opportunistically each summer 2019-2022, with five site visits 2019-2021 and six site visits in 2022. We measured pellet length and width and subjectively assessed pellet condition. We dried samples after collection and stored them in breathable envelopes before extracting and genotyping DNA at the Epps Population and Conservation Genetics Laboratory at Oregon State University. We did not attempt to genotype samples judged to be from young of the year. We used a nine loci microsatellite panel, plus a sex marking loci, to initially identify unique individuals from the DNA extracted from samples and extended the microsatellite panel to 16 loci (excluding sex) for one sample from each uniquely identified animal. We collected a total of 2166 fecal samples across the four seasons (527 in 2019, 517 in 2020, 579 in 2021, 531 in 2022) and attempted to genotype 1558 samples (316 in 2019, 393 in 2020, 403 in 2021, 467 in 2022). Genotyping success declined over time (88% in 2019, 78% in 2020, 62% in 2021, 62% in 2022). Using the 9-loci microsatellite panel, we identified 97 individuals (58 females, 33 males, 6 unsexed) in 2019, 127 (67 females, 51 males, 9 unsexed) in 2020, 104 (55 females, 44 males, 5 unsexed) in 2021, and 123 (53 females, 43 males, 18 unsexed) in 2022. Extension of genotypes to 16 loci for 139 samples collected 2019-2021 elucidated that genotyping errors related to sample quality (allelic dropout) created Type I errors in animal identification, where multiple samples from one animal were incorrectly determined to be from different animals. After we corrected for known instances of this error, the number of individuals identified was reduced to 89 in 2019, 107 in 2020 and 98 in 2021. These counts were similar to winter helicopter total counts corresponding to the same years, which were 81, 100, and 90. To ensure that individuals are accurately identified, we are extending genotypes of all individuals identified with the nine loci panel to 16 loci. We will subsequently fit the resulting dataset into a capture-recapture framework to estimate abundance, survival, and reproduction. Although preliminary findings have revealed challenges of using fecal genetics to monitor bighorn sheep in the Teton Range, we anticipate this non-invasive approach to monitoring will yield demographic estimates of comparable accuracy and precision to approaches that require capturing and tagging individuals.

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KEY WORDS: bighorn sheep, capture-recapture, demographics, fecal DNA, fecal genetics, mark-recapture, non-invasive, population monitoring.

Teton Range Bighorn Sheep and Winter Recreation Collaborative Process: Successes and Struggles

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ABSTRACT: The Teton Range bighorn sheep herd is a small, isolated population of approximately 125 sheep located in the Teton Mountain Range. The herd lost access to its traditional migration routes and low elevation winter ranges approximately 70 years ago due to human development and now lives at high elevations in both summer and winter. Winter habitat is limited to relatively small patches of wind-scoured ridges and south-facing slopes. The herd's range overlaps multiple jurisdictions and is cooperatively managed by the Teton Range Bighorn Sheep Working Group. In recent years, the herd has been pressed by a rapidly growing winter human activity: backcountry skiing. Past research has shown that Teton Range bighorn sheep avoid areas where backcountry skiing occurs, even if the area is relatively high quality winter habitat. The increase in backcountry skiing and impacts to bighorn sheep is a top concerns for managers, however at the same time, backcountry skiing in the Tetons has a rich history, is highly valued by the local community, and is iconic on an international scale. Restricting access would be very controversial. Therefore, beginning in 2017, the working group decided to develop a public collaborative process that would engage the community in finding solutions to balance bighorn sheep winter habitat needs with winter recreation. This effort included over 30 one-on-one "coffee-cup" conversations with key stakeholders and influencers and five public workshops to which over 150 people attended. These efforts culminated in a final report that the working group released in October 2021 with over 60 specific recommendations, including sitespecific winter range closures, designated travel routes, habitat treatments, and public education and engagement. This presentation will share some of the specific successes and struggles that we encountered during this process and recommendations for other managers interested in similar efforts.

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KEY WORDS: backcountry recreation, collaborative process, Rocky Mountain bighorn sheep, skiing, Wyoming.

Landscape Factors Inhibiting Mountain Goat Movements: A Contribution to Delineating Demographic Units

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ABSTRACT: Because mountain goat (*Oreamnos americanus*) populations are sensitive to anthropogenic mortality, managers of recreational harvests typically restrict hunting opportunity to a small percentage of estimated abundance within some defined boundary (and often, only if abundance meets a defined minimum). In addition to difficulties of estimating abundance in the field, goat managers face uncertainty in geographically delineating where one "population" ends and another begins. Mountain goats typically remain close to steep escape terrain, yet they are sometimes seen in atypical habitats and occasional migrants are known to traverse considerable distances across inhospitable terrain. Molecular approaches provide understanding of barriers to gene flow, but aggregations that can potentially be overexploited likely operate on smaller spatio-temporal scales. Managing a small subset of goats may understate the scale on which demography operates; conversely, managers may face pressure to aggregate units inappropriately. Localized, detailed information to answer these questions are unavailable, and goats exhibit considerable heterogeneity in movement patterns. Thus, we used of GPS-collar data from 184 mountain goats from previous studies in Washington and Montana to quantify movement patterns that may be generalizable across their range south of Alaska. We used U.S. Forest Service digital maps of unconfined valley bottoms (Nagle et al. 2014) as a common currency to quantify goats' willingness to cross atypical habitat, and thus provide a proxy for topography likely to constrain populations at the management scale. As expected, mountain goat movement paths (reflecting ~ 285 goat/years of data) rarely intersected unconfined valleys, particularly those larger than 100 ha in size ($\bar{x}$ = 0.007/goat/year). This suggests that unconfined valleys, as defined, may provide useful surrogates of barriers to movement at the demographic spatio-temporal scale. Such valleys would not appropriately be used directly as demographic unit boundaries, but because they are mapped across the U.S. Northern Rockies can be referenced in assessing if goat hunting boundaries are likely to encompass > 1 demographic unit.

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KEY WORDS: delineating discrete populations, Montana, mountain goats, Washington.

INTRODUCTION

Because of their slow rates of increase, weak responses to reductions in density, and the difficulty of limiting recreational harvest only to males, mountain goat populations are sensitive to anthropogenic mortality (Toweill et al. 2004, Hamel et al. 2006). Indeed, excessive harvest by legally permitted hunters is generally accepted as a primary cause for historic declines in abundance (Mountain Goat Management Team 2010, Rice and Gay 2010). This is particularly true among native populations, albeit somewhat less so among introduced populations (DeCesare and Smith 2018). Mountain goats (goats, hereafter) also face increasing stress from climate change (Pettorelli et al. 2017, White et al. 2018, Sarmento et al. 2019) and, in some areas, changes in the make-up and behavior of their predators (Lehman et al. 2020). That said, goats are classified as a game species in most jurisdictions where they are present, and wildlife agencies and Indian tribes face the challenge of providing hunting opportunity when possible while avoiding overharvest. Indigenous tribes may also wish to pursue customary and traditional consumptive use of goats without inducing population declines (Jessen et al. 2021).

In response, many jurisdictions have adopted generalized guidelines to assist managers in setting harvest quotas. These typically include metrics guiding offtake rate (e.g., proportion of the total population deemed safe to remove annually), as well as minimum abundance at which a population can be considered eligible for recreational harvest (e.g., McDonough and Selinger 2008, Toweill et al 2004, Mountain Goat Management Team, 2010). But even if such metrics are based on rigorously conducted analyses and field surveys, the question often remains as to exactly what geographic areas contain goats that compromise a demographic unit (Caughley 1977), i.e., “a biological unit at the level of ecological integration where it is meaningful to speak of a birth rate, a death rate, a sex ratio and an age structure in describing the properties of the unit.” Goat “populations”, particularly those inhabiting large blocks of contiguous mountain habitat, can be challenging to identify.

If there are policies for providing hunting opportunity when biologically sustainable, as well as for larger rather than smaller geographic units, how does one know if the search for some number of goats (e.g., 50 or 100) would result in inappropriately aggregating animals that don't actually function as a demographic unit? Conversely, if one assumes that only animals consistently known to be associating with one another can be considered a demographic unit (e.g., Sevigny et al. 2021), would such aggregations overlook demographic connectivity occurring on larger spatio-temporal scales? These characteristics of goat social structure and sensitivity to harvest beg a difficult question: What, in any given geographic area, is the appropriate spatial extent over which it is appropriate to consider that animals share birth and death rates (and thus expect that they will respond somewhat predictably to any given rate of hunting mortality)?

Although it is well established that goats are tightly tied to escape terrain, the advent of GPS collaring and molecular techniques has revealed that goats occasionally make long-distance movements, sometimes crossing atypical habitats (Smith and Raedeke 1982, Rice 2010). An appealing and intuitive response to the question posed above is to capture and place GPS-collars on goats in and near the geographic region of uncertainty and to evaluate potential boundaries delimiting demographic units based on these local data. Although local and updated information is always useful, small sample size may result in overlooking movements that effectively link group of goats. Here we are interested in understanding characteristics of unusual movements that may, despite their rarity, function to link individuals via interbreeding and/or coping with mortality risks sufficiently similar to justify considering them as belonging to a single demographic unit.

Advances in landscape genetics have yielded considerable insight into population structure of goats in specific areas (Shirk et al. 2010, Shafer et al. 2012, Shirk and Cushman 2014, Parks et al. 2015, Wolf et al. 2020, White et al. 2021). When available, this information on gene flow provides valuable insight for population managers, and should be considered.

However, it seems likely that the dynamics that ultimately inform demographic rates operate on shorter-temporal and finer geographic scales than those illuminated by metrics of genetic relatedness (Palsbøl et al. 2006, Lowe and Allendorf 2010). Occasional effective migrations can function to connect aggregations of animals genetically that otherwise cope with different mortality risks, and/or that commonly (if not exclusively) form separate breeding units (Mills and Allendorf 1996, Wang 2004). It would seem quite possible for a manager to inadvertently over-harvest animals if they are incorrectly assumed to be part of a larger group (or a group with higher productivity) even in the absence of any genetic differentiation.

Alternatively, one may gain insight (although not certainty) regarding the likely dynamics among animals in a localized area from any generalizable patterns that are observed consistently in a large sample of animals that may not necessarily be apparent from a small sample from the particular area of interest. In this study, we asked if one or more “common geographic currencies” could be identified that could serve as proxies to the ideal (but unattainable) determinants that serve to differentiate units of animals to which the abstractions of vital rates might usefully apply. A small contribution toward this end may be better understanding movement patterns of individual goats because even if we lack the ability to identify populations we know that they consist, ultimately, of individuals. We know without further examination that most goats stay in relatively small areas most of the time (an important exception being those who travel long distances to mineral licks; Poole et al. 2010, Rice 2010, Kroesen et al. 2020). We also know that -- sometimes - goats (usually but not always young males) make atypical movements, crossing terrain that goats usually avoid. Here we ask if there are patterns we can glean from these movements that would help us answer the question: "What geographic features are likely to delimit goat 'populations' (at the temporal scale relevant to a biologist interested in keeping mortality rates sustainable)"?

Roads used by motorized vehicles are an obvious candidate for such a common currency, and have been implicated as drivers of genetic isolation in both bighorn sheep (*Ovis canadensis*; Epps et al. 2005) and goats (Parks et al. 2015). However heavily travelled roads are rare within most goat habitat, and thus likely to be relatively insensitive barometers of constraints to movements at a fine scale. Thus, we also consider here a metric termed unconfined valleys (Nagle et al. 2014). This metric was developed to aid land managers in understanding ecological processes that may differ depending on valley morphology. Confined valleys are “typically narrow and v-shaped…have relatively steep, erosive gradients, and….little to no floodplain...In contrast, unconfined valleys are wider depositional areas, with extensive alluvial fill and broad floodplains” (Nagle et al. 2014). Although neither the rationale nor algorithm for identifying unconfined valleys have anything to do with goats or their fidelity to escape terrain, we reasoned that such valleys might function as an objective and readily available proxy for landscape features that limit goat movements. Essentially, whereas we typically focus on the steep (and typically locally-highest elevation) areas where goats spend more of their time, here we turn the tables, and focus on the flattest (and typically locally-lowest elevation) areas. Whereas we know that goats can and do descend to move among patches of steep escape terrain, we ask here whether there are landscape features that characterize (or, if possible, even define) areas that goats do not use, and thus may contribute to isolation among aggregations of individuals.

METHODS

We obtained and mapped travel routes of free-ranging goats, using existing data from goats that had been outfitted with GPS collars, regardless of the collars’ fix acquisition frequency. We obtained and mapped both roads ("USA Major Roads", ESRI, Tele Atlas of North America), and unconfined valleys (Nagle et al. 2014; https://www.fs.fed.us/rm/boise/AWAE/projects/valley_confinement.shtml). Using ArcGIS, we then queried each movement path for whether it intersected a road or unconfined valley (and if the latter, the area of the valley intersected). Data came from studies in Washington State (Rice 2008, 2010; Vales et al. 2016; Harris et al. 2022), and Montana (J. Cunningham, Montana Fish, Wildlife and Parks, unpublished; F. Hayes, Colorado State University, unpublished). We defined resident goats as those who had not been translocated (even if their ancestors had been), and introduced goats as those who had earlier been translocated from their natal ranges. We lacked data on ages of goats in the sample, but only a few were younger than 2 years-of-age.

GPS collars were programmed in response to each study's unique objectives. Both Montana studies programmed collars to obtain locations every 4 hours, whereas almost all translocated animals in Washington were programmed to obtain locations every 23 hours (the exception being a handful in the final year of the project programmed to obtain locations every 12 hours). Most collars used in studies by Rice (2008, 2010) were programmed to obtain locations every 3 hours, but some had variable fix schedules depending on season. In all cases, missed fixes resulted in longer achieved intervals between locations than programmed (Table 1). For Montana goat data, we first filtered for data quality, removing all locations with DOP > 2. For Washington data, we removed records for DOP > 4. Additionally, we visually inspected each movement route, and removed clearly anomalous locations that were individual points unaccompanied by any other points anywhere close. For translocated data, we removed all locations < 1 year from the date of release to limit the influence of exploratory movements (e.g., Fryxell et al. 2008, Werdel et al. 2021, Harris et al. 2022 specifically for these animals). Most goats descend to lower elevations in winter and use forested terrain more than in summer (Poole and Heard 2003, Rice 2008), and breeding occurs only during late October—early December, suggesting this time period might best be isolated when examining potential constraints to movement (but see Richard et al. 2014 for an example in which males did not move among previously identified subpopulations). However, the rarity with which goats move away from escape terrain appears similar year-round (Poole and Heard 2003, Rice 2008). We also reasoned that at least some influences on survival (which should be similar among animals constituting a demographic unit) occur year-round. Therefore, all analyses used goat locations year-round.

We characterized goat location paths by 1) gender; 2) whether the goat was resident or introduced to the area (albeit > 1 year earlier); and 3) geographic area (of which there were 4: Glacier Park, Montana; Bridger Mountains Montana; Washington Cascades north of Interstate Highway 90 (I-90, hereafter); and Washington Cascades south of I-90). We also noted some cases in which goats were associated with known mineral licks (Rice 2010, Kroesen et al. 2020).

To determine if any avoidance of unconfined valleys and major roads by goats was not simply an artifact of these features being rare within their overall geographic range (they appeared to be, Figure 1), we created and mapped randomized goat movement paths to act as a null hypothesis for comparison. For each documented movement path of resident (i.e., non-translocated) goats in Washington State, we generated 3 pseudo-paths by offsetting each actual path in a random direction and distance, with the offset distance randomly selected from a normal distribution with standard deviation of 10 km. These 153 paths represented 'goatlike' movement paths within the general area used by each goat (i.e., with the same number, direction, and length of each individual path segment as the actual goat but independent from the underlying

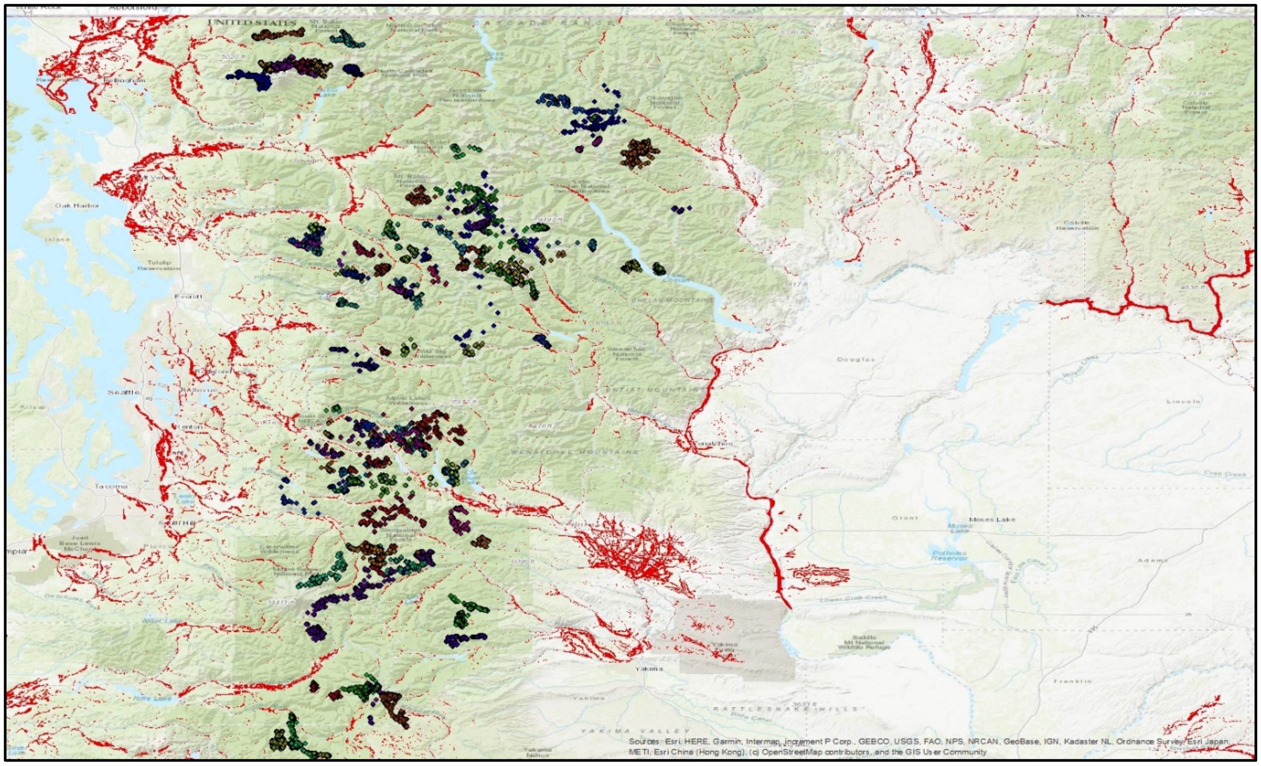


Figure 1. Topographic map of the western Washington, USA, showing locations from GPS-collared mountain goats (dots) and unconfined valleys (Nagle et al. 2014, red polygons).

topography). This analysis was analogous to investigating selection at the 3rd order level given evidence of selection at the 2nd order (*sensu* Johnson 1980). To test whether observed frequencies of unconfined valley and road crossings differed from the crossing frequencies of these random paths (i.e., assumed to quantify the expectation under the null hypothesis of no selection at the finer geographic scale), we used generalized mixed models with both gender and whether the path was north or south of I-90 as interacting fixed covariates, a negative binomial error structure, and individual goat as a random factor (package glmer, R version 4.0.4). To test whether observed and random paths differed in the area of unconfined valleys intersected, we used generalized linear mixed models with Gaussian error structure with goat as a random factor (package lmer, R version 4.0.4.).

RESULTS

Available data

The data set (Table 1) consisted of 184 movement paths from GPS-collared goats, of which 51 (36 ♀,15♂) were residents in Washington's Cascades, 12 (9♀, 3♂) were residents in Montana's Bridger Range, and 24 (19♀, 5♂) were residents captured in Glacier National Park, Montana (together totaling 153.4 goat/years of monitoring;171,575 locations); as well as 97 movement paths of goats (60♀, 37♂) surviving at least one year after having been translocated into Washington's Cascades from the Olympic Mountains and the Elkhorn Mountains in Oregon (representing 130.6 goat/years of monitoring; 36,204 locations).

Crossings of unconfined valleys overall

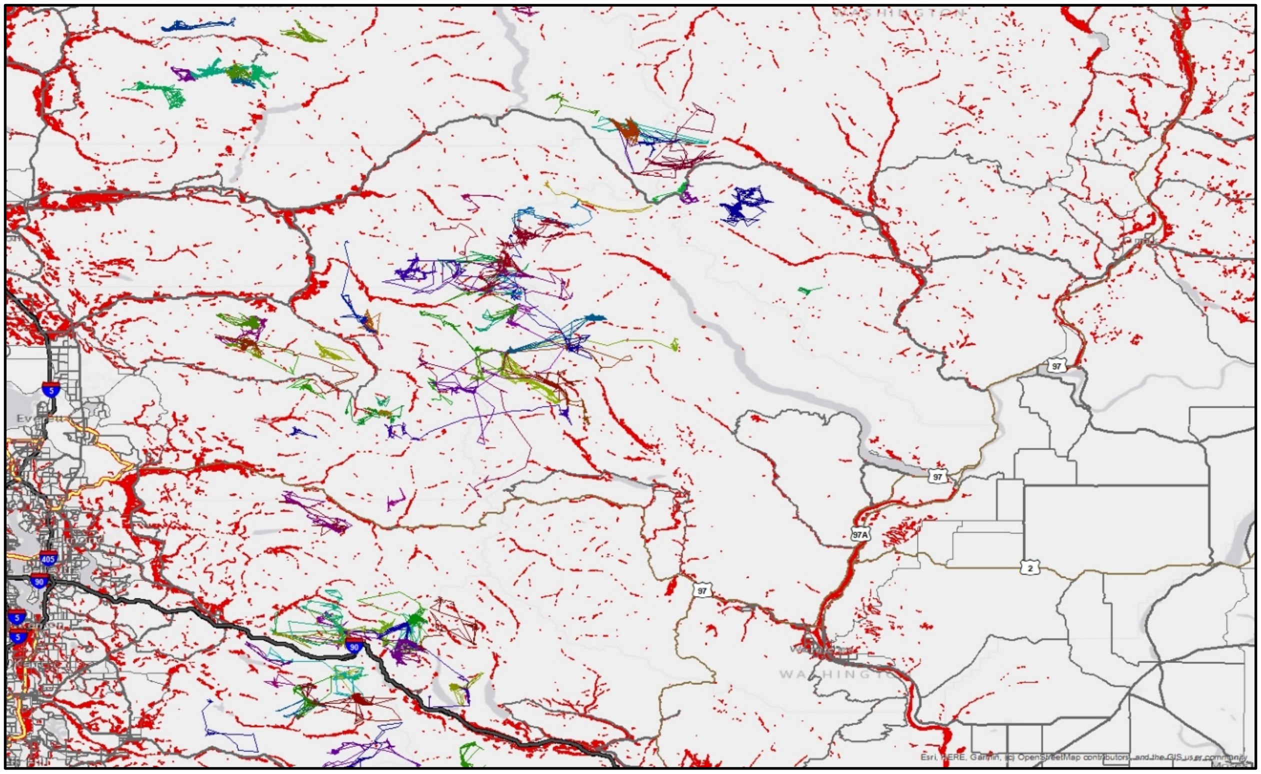
Movement paths of goats generally avoided unconfined valleys and roads (Table 2, Figure 2).

Table 1. Sample sizes of mountain goat movement paths and achieved GPS fix intervals used in the analyses. Region: WA = Washington, N = north of I-90, S = south of I-90, Status; R = resident, T = translocated. Highways include state and US highways.

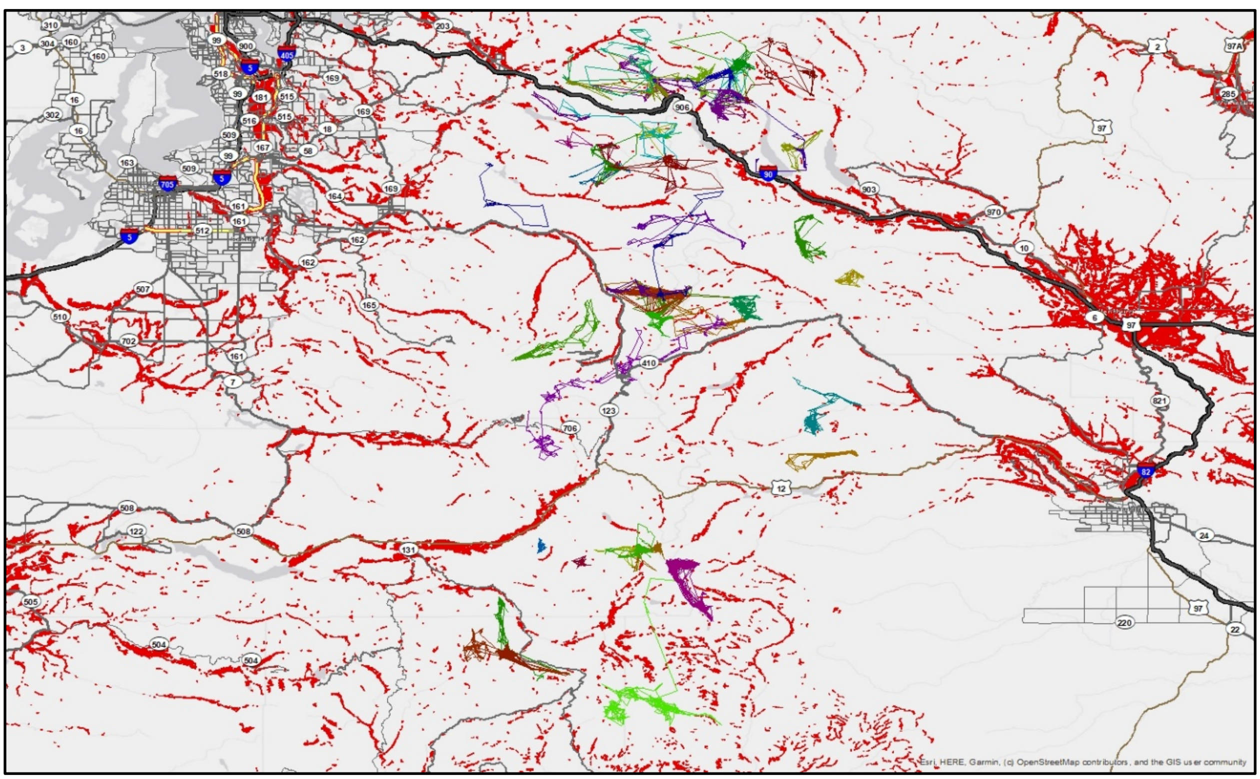
Region	Status	Females	Males	Years monitored	Path segments	Fix Interval hrs ($\bar{x}, SD$)
WA–N	R	24	3	47.8	35,545	14.8 (7.6)
WA–S	R	13	11	46.9	30,878	16.2 (10.3)
WA–N	T	48	32	103.8	29,013	35.8 (9.7)
WA–S	T	12	5	26.8	7,191	35.5 (15.1)
Bridger	R	9	3	12.9	26,287	4.3 (0.4)
Glacier	R	19	5	45.9	78,865	5.1 (0.4)
TOTAL		125	59	284.1	207,779	

Table 2. Summary of mountain goat movement paths and summaries of unconfined valleys and highways crossed. Region: WA = Washington, N = north of I-90, S = south of I-90, Status; R = resident, T = translocated. Highways include state and US highways.

Region	Status	Valley crossings (all)	Valley Crossings (> 1 km^2)	Valley Crossings (0.5-1 km^2)	Valley Crossings (> 0.25 -0.5 km^2)	Area of valleys crossed ($\bar{x}$)	Highway crossings
WA–N	R	6	0	0	0	0.015	0
WA–S	R	33	0	0	2	0.101	2
WA–N	T	53	2	5	3	0.214	2
WA–S	T	16	0	0	0	0.036	0
Bridger	R	0	0	0	0	0.000	0
Glacier	R	17	0	0	0	0.016	6
TOTAL		123	2	4	4	0.109	10



a.



b.

Figure 2. Paths of GPS-collared mountain goats (various colors) and unconfined valleys (red polygons, Nagle et al. 2014) in Washington State, a) north of I-90 and b) south of I-90.

Overall, goats crossed unconfined valleys at a mean rate of 0.441/goat/year. Among all goats, 118 (64%) made no crossings of unconfined valleys and of the 66 that did, only 2 crossed unconfined valleys larger than 1.0 km^2 ($\bar{x}$ = 0.007/goat/year). An additional 5 crossings were of unconfined valleys >0.5 km^2<1.0 km^2 ($\bar{x}$ = 0.018/goat/year), and 6 crossings were of unconfined valleys between 0.25 km^2 and 0.5 km^2 ($\bar{x}$ = 0.021/goat/year). The mean size of unconfined valleys crossed by all goats was 11.4 ha (SD = 56.4 ha, Figure 3).

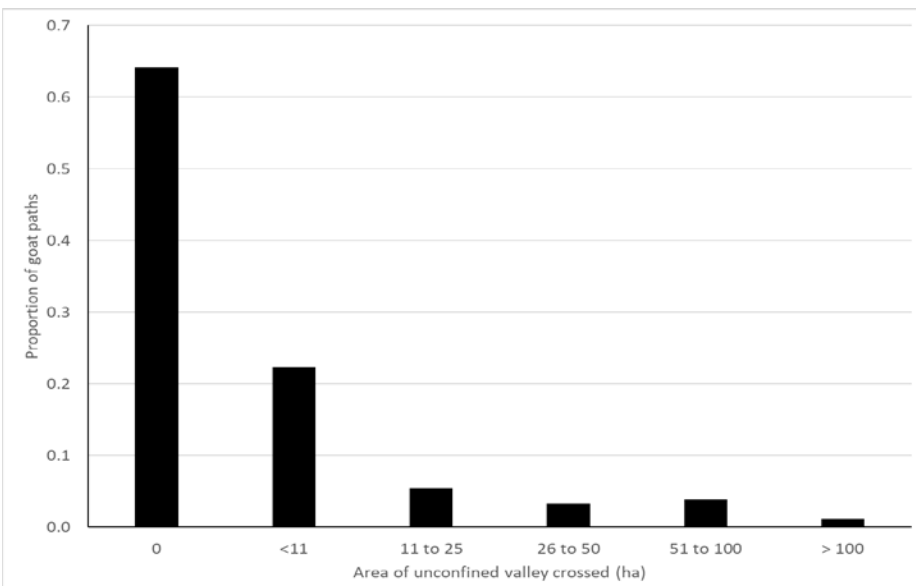


Figure 3. Proportion of unconfined valleys of various sizes (area in ha) crossed by mountain goats monitored by GPS collars. See text for details.

Crossings of highways and other major roads

Crossings of major roads and highways were rare. No goat movement paths crossed I-90 (the only highway of this class within, or adjacent to, the study areas). Washington State Highways 20, 92, 410 and 706 were crossed once each. Four of the 6 goats captured in the southern part of Glacier National Park (near the Walton salt lick) crossed US Highway 2, which has been identified as a partial barrier to movement from grizzly bears (*Ursus arctos*; Waller and Servheen 2005). However, 2 of these 4 appeared to use primarily (and perhaps exclusively) the underpass that was built, in part, to allow goats safe access to the salt lick (Singer and Doherty 1985). Crossings of minor forest roads were not quantified (in some cases, were not mapped), but appeared to be common.

Crossings of unconfined valleys by geography

Examining the geographic origin of the sample more closely, none of the 12 goats monitored in the Bridger Mountains crossed unconfined valleys (habitats used by goats in the Bridgers included none, Figure 4). Among resident goats in Washington, the 23 living in the relatively gentler terrain south of I-90 accounted for 34 of 39 total unconfined valley crossings, whereas only 5 crossings of unconfined valleys were documented from the 28 goats living north of the highway where steep terrain is more contiguous. Among translocated goats, the frequency of unconfined valley crossings among animals south of I-90 was 0.60/goat/year, compared with 0.51/goat/year for animals north of highway. The cumulative area of unconfined valleys crossed by goats north of I-90 (17.11 km^2, 0.16 km^2/goat/year) was larger than among goats living south of the Highway (0.60 km^2, 0.02 km^2/goat/year). However, 10.6 km^2 (> 62%) of the total unconfined valley area crossed by goats north of the Highway was due to just 2 animals (1♀, 1♂), each of which made roundtrips across narrow sections of linear (but large) unconfined valleys (Figure 5). Were these 2 movement paths to be considered outliers and redacted, total areas of unconfined valley crossed/goat/year by goats north of the Highway

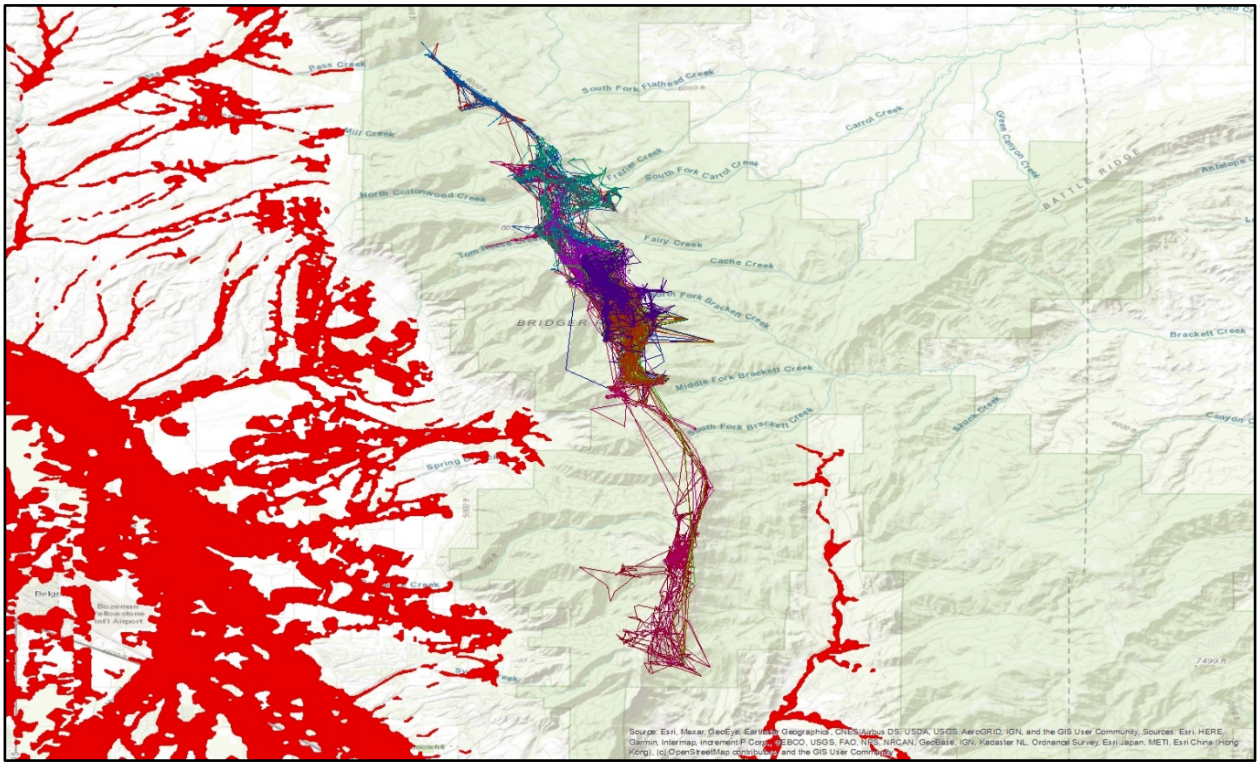


Figure 4. Movement paths of GPS-collared mountain goats (various colors) in the Bridger Mountains, SW Montana. Unconfined valleys (Nagle et al. 2014) in red polygons.

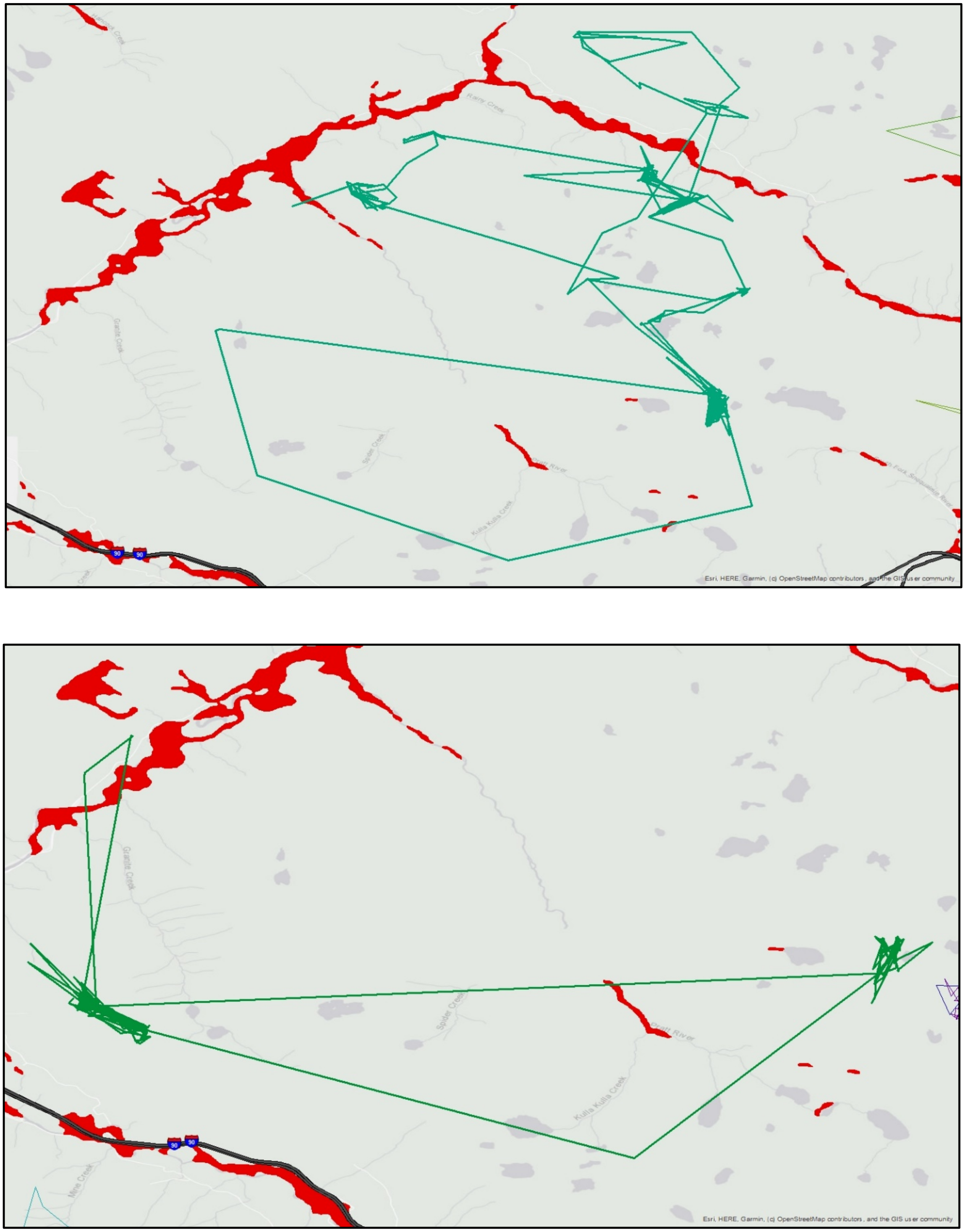
(6.55 km^2, 0.07/goat/year) was closer to the value observed among goats south of the Highway. The 24 goats captured in Glacier National Park (4 of which also used adjacent portions of the Flathead National Forest) accounted for 17 unconfined valley crossings, but the valleys crossed tended to be small ($\bar{x}$ = 1.6 ha). Small sample size prohibited testing whether goats known to use salt licks differed in frequency of crossing valleys or roads from those with unknown lick use (although most appeared, qualitatively, to travel extensively to and from lick sites).

Crossings by gender and residency status

Movement paths of males were more likely to cross unconfined valleys (0.78/goat/year) than females (0.30/goat/year; see Appendix for statistical support). Data did not support there being a gender difference in likelihood of crossing highways or major roads. Crossings of unconfined valleys by translocated goats (0.53/goat/year) did not differ significantly from crossings by resident goats (0.36/goat/year; see Appendix).

Observed vs. random paths (null model)

Actual goat paths crossed unconfined valleys less frequently than randomized paths (Table 3), both in a model paired with I-90 (random path = 1.827, SE = 0.397, z = 4.598, P < 0.001; south of I-90 = 1.597, SE = 0.502, z = 3.183, P = 0.001, interaction not significant), and in a model paired with gender (random path = 1.303, SE = 0.265, z = 4.917, P < 0.001; male = 1.328, SE = 0.471, z = 3.109, P = 0.002, interaction not significant). In examining only large (i.e., area > 1 km^2) unconfined valleys, actual goat paths were even less likely to cross than random goat paths (random path = 21.503, SE = 1.303, z = 16.509, P < 0.001; south of I-90 = 1.013, SE = 4.257, z = 0.238, ns; interaction not significant), and paths of males crossed these



a.

b.

Figure 5. Movement paths of 2 mountain goats wearing GPS collars that crossed large (1 km^2) unconfined valleys, exceptions to the finding of this investigation that such crossings were rarely observed. Both panels A and B depict the area just north of I-90 in the Snoqualmie River drainage.

Table 3. Summary statistics of observed movement paths of resident mountain goats in Washington State (*n* = 51) and randomized versions of these paths (*n* = 153), showing mean and standard errors of number of crossings of unconfined valleys, number of crossings of large (>1-km^2) unconfined valleys, number of crossings of important local roads, and number of crossings of state highways.

Crossings	**Observed movement paths**	**Random movement paths**
Mean (SE) unconfined valley crossings	0.76 (0.21)	2.56 (0.26)
Mean (SE) large (> 1-km^2) unconfined valley crossings	0.00 (0.00)	0.31 (0.05)
Mean (SE) important local road crossings	0.02 (0.02)	0.11 (0.03)
Mean (SE) state highway crossings	0.02 (0.02)	0.16 (0.03)

large valleys more frequently than those of females (random path = 1.153, SE = 0.295, z = 4.917, $P < 0.001$; male = 1.328, SE = 0.427, z = 3.109, $P = 0.002$; interaction not significant). Results (not shown) were similar when examining paths crossing important roads and state highways. (US highways and were not crossed frequently enough for meaningful analyses).

DISCUSSION

Examining a large data set created by combining goat movement paths from different research projects in diverse geographic settings yielded some important insights. Importantly, although some goats traveled considerable distances (and even occasionally emigrated from their place of birth to other goat habitat separated by areas devoid of escape terrain), they rarely crossed large-sized valley bottoms or heavily-used highways to do so. Although narrow, steep-sided valleys did not necessarily inhibit frequent goat movements, broad valleys were very rarely traversed (and when goats moved to steeper terrain on either side of broad valleys, they did so by going around them). This finding is unsurprising, as it confirms and reinforces goats' well-accepted characteristic of fidelity to steep escape terrain (Shafer et al. 2012, Wolf et al. 2020). Mapping it in this way, however, allows one to clearly visualize not only places goats will use, but also places they will not use, even in the absence of site-specific or genetic data.

A plausible interpretation is that this exercise has taught us nothing more than that goats inhabit mountainous terrain where flat valleys larger than a few hectares are rarely found in any case. However, the finding that observed movement paths were significantly less likely to cross large valleys than movement paths randomly drawn from within their mountain habitats suggests that goats make conscious choices to avoid those few valleys they could potentially cross while moving among safe foraging and resting locations.

Considering goats' infrequent use of broad valleys leads to some nuance in interpreting the isolation among goat populations associated with heavily used highways (Shirk et al. 2010, Parks et al. 2015). Although it is likely that motorized traffic (or possibly associated fencing) directly inhibits highway crossing, major highways in this study were generally associated with large unconfined valleys that were avoided whether or not they contained highways. Thus, goats may have had two reasons for hesitancy in crossing highways: 1) traffic disturbance itself, and 2) tendency to be located relatively far from steep terrain. This suggests that crossing structures built to encourage connecting genetically-isolated populations may be unsuccessful if built where the inherent topography discourages goat use.

There may be other, better proxies than unconfined valleys, as defined and mapped by Nagle et al (2014) to predict obstructions to free movement of goats. Advantages of this metric are that is objective, well-documented, and already mapped for almost all goat habitat in the contiguous U.S. states (Washington, Oregon, Idaho, Montana, and northwestern Wyoming). The published algorithm should allow for similar mapping and use elsewhere.

MANANGEMENT IMPLICATIONS

Neither unconfined valleys nor major roads, by themselves, provide sufficient information to demarcate the boundaries of demographic units for goats; at best, they provide insight and can function as part of a comprehensive assessment incorporating locally-unique factors. It would be simplistic (and probably unfeasible) for mangers to use either unconfined valleys or major roads as sole criteria for demarcating population boundaries. Because some landscapes evidently allow goats to circumvent rather than travel through broad valleys, the mere presence of an unconfined valley does not provide an unambiguous signal indicating where demographic connectivity is lacking. By the same token, our data would not support the inference that the lack of an unconfined valley guarantees demographic connectivity. That said, these results suggest that although goats occasionally move through terrain lacking escape terrain, they very rarely cross large valleys or major roads to do so. Thus, we recommend that managers uncertain about the validity of assumed goat population units examine maps with that include both these features. Where extensive areas of unconfined valleys occur within a region considered contain a single demographic unit, additional consideration should be given to the possibility that goats separated by them may interact with one another too rarely to function as a single unit.

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APPENDIX

Because the sample of goat movement paths was not a random sample of the universe of possible paths that might inform extrapolation to unstudied areas, we examined simple models to see if crossings and/or area crossed differed by gender, region, or resident vs. translocated goats. Important differences among these factors would suggest caution in extrapolating the summary results and inferences from this study. Conversely, few, or minor differences would suggest that the sample used was a reasonable surrogate for a truly random sample from all goats to which inference might be applied (which, needless to add, would be nearly impossible to obtain).

To this end, we developed general linear models (glm) with candidate predictors gender, region (WA N, WA S, Glacier, Bridgers), resident vs. translocated, and mean fix interval of each goat path, weighted by the number of years monitored. For models examining frequency of crossings per goat, we assumed a negative binomial error structure; for models examining the dependent variable area crossed (a continuous variable), we assumed a Gaussian (normal) error structure. We compared models with all reasonable combinations of predictor variables using AIC, and considered predictors significant at $\alpha = 0.05$.

In univariate analyses of crossing frequency, we found no effect of residency, region, or mean fix interval at the nominal level of significance. However, there was evidence that gender affected unconfined valley crossing frequency (male effect = 0.831, SE = 0.248, $t = 3.224$, $P = 0.001$). In univariate analysis of area of unconfined valleys crossed, no predictors were significant at the nominal level. In multivariate models of unconfined valley crossing frequency, almost all AIC model weight was taken by the top model, which included effects of residency, region, gender, and mean fix interval. However, in this top model, only gender (as in the univariate model) and mean fix interval (interval = 0.019, SE = 0.009, $z = 2.171$, $P = 0.030$) were significant. In multivariate models of area of unconfined valley crossed, the model with both gender and residence was the top AIC model, but neither predictor was significant at the nominal level.

In summary, these results provided some assurance that the general results found in the body of the paper (i.e., that unconfined valleys are crossed rarely, that large unconfined valleys are crossed extremely rarely, that interstate highways are almost never crossed, and the US and other high-use highways are very rarely crossed) are not highly dependent on characteristics of the (non-random) sample used. The only strong effect found was that males cross valleys more readily than females, but the ratio of > 1-year old females to males in the sample (~ 2:1) is probably not greatly different from that found in most unsampled free-ranging populations. Thus, our sample is probably a reasonable reflection that males are more willing to cross these valleys than females. We also found some indication that GPS fix frequency affected valley crossing frequency, with movement paths connecting fixes further in time from each other more likely to cross an unconfined valleys than paths connecting fixes obtained in closer temporal sequence. This suggests that some mapped valley crossings may have been artifacts of missed data fixes (i.e., animals may have avoided these valleys, but a straight line connecting two locations many hours apart resulted in a valley intersection). This effect renders our conclusions conservative. That is, goats with no history of having been translocated will cross unconfined valleys and highways somewhat less frequently than indicated by the sample in this study taken as a whole.

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Early Summer Precipitation and Temperature Associated with Mountain Goat Declines in Glacier National Park

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ABSTRACT: A shifting climate poses threats to alpine-adapted species including mountain goats. We used a 12 year citizen science dataset and a Bayesian N-mixture model to estimate population trend and factors associated with trend of mountain goats in Glacier National Park. Median goats per site declined by 45% (95% CRI = 32%, 57%) from 77.8 (95% CRI = 64.4, 95.1) in 2008 to 42.3 (95%CRI = 34.3, 52.2) in 2019, with consistent declines from 2008 until 2015, when the number of estimated goats stabilized. The >30% decline over only 2 generations exceeds IUCN criteria for classifying a population as vulnerable. Climate variables had the greatest association with population growth rate, particularly precipitation between May 15 and June 15 of the previous summer, the neonatal period. Greater growth occurred with greater snow water equivalent, mean winter temperature, early summer temperature and early summer precipitation. In addition, the proportion of permanent snow and glaciers and the presence of natural mineral licks strongly influenced initial abundance of goats. We are not able to determine the relative contribution of vital rates to this apparent decline. However, the results are consistent with the pattern of kid to nanny ratios across time. Our results also suggest ways to improve detection rates during visual goat surveys, which is important for precision of estimates. Retention of observers with experience, consistent use of a spotting scope, and conducting surveys at lower temperatures and earlier dates could all increase detection for the citizen science program. This will be particularly important given the lower number of goats currently observed in the park. Research to estimate the population size, assess population fluctuations, evaluate genetic structure, assess changing habitat, human recreation levels and forage, and to forward project climate effects on persistence will be crucial to understanding the context of these results and conserving this iconic, meta-population at the southern edge of the distribution of native mountain goats.

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KEY WORDS: climate effects, Glacier National Park, mountain goats, population trend.

Demographic Uncertainty and Disease Risk Drive Climate-Informed Mountain Goat Management

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ABSTRACT: Scientists and managers have raised concerns about mountain goat populations in many areas in recent years. Both climate change and respiratory pathogens associated with widespread pneumonia epidemics in bighorn sheep may negatively affect mountain goat populations. Mountain goat demographic and population data are difficult to collect and sparsely available, making population management decisions difficult. We developed predictive models incorporating these uncertainties and analyzed results within a structured decision making framework to make management recommendations and identify priority information needs in Montana, USA. We built a resource selection model to forecast occupied mountain goat habitat and account for uncertainty in effects of climate change, and a Leslie matrix projection model to predict population trends while accounting for uncertainty in population demographics and dynamics. Additionally, we predicted disease risks while accounting for uncertainty about presence of pneumonia pathogens and risk tolerance for mixing populations during translocations.

Our analysis predicted that new introductions would produce more area occupied by mountain goats at mid-century, regardless of the effects of climate change. Population augmentations, carnivore management, and harvest management may improve population trends, although this was associated with considerable uncertainty. Tolerance for risk of disease transmission affected optimal management choices because translocations are expected to increase disease risks for mountain goats and sympatric bighorn sheep. Expected value of information analyses revealed that reducing uncertainty related to population dynamics would affect the optimal choice among management strategies to improve mountain goat trends. Reducing uncertainty related to the presence of pneumonia-associated pathogens and consequences of mixing microbial communities should reduce disease risks if translocations are included in future management strategies. We recommend managers determine tolerance for disease risks associated with translocations that they and constituents are willing to accept. From this, an adaptive management program can be constructed wherein a portfolio of management actions are chosen based on risk tolerance in each population range combined with the amount that uncertainty is reduced when paired with monitoring, to ultimately improve achievement of fundamental objectives.

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KEY WORDS: carnivore management, climate effects, disease risk, harvest, Montana, mountain goats, population augmentation, population trend.

Diagnostic Strengths of Strain Typing Bacteria During Surveillance and Bighorn Sheep Die-offs

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ABSTRACT: The etiology of bighorn sheep respiratory disease is often questioned when the suspected bacterial pathogen is found in both healthy and diseased individuals. Several approaches have been employed to investigate pathogens at a sub-species level, in attempt to understand virulence differences. Examples identifying genetic differences include detecting the presence or absence of certain genes such as leukotoxin (Shanthalingam et al. 2013) and measuring relatedness through multilocus sequence typing (MLST; Kamath et al. 2019). Historically, functional assessments of bacterial isolates using biochemical testing have been utilized to identify associations between biogroups and die-offs (Wolfe et al. 2010). However, most bighorn sheep disease surveillance programs focus on identifying the prevalence of common bacterial pathogens. This routinely involves bacterial culture and PCR. Recently, mass spectrometry (MALDI) has been introduced into diagnostic workflows following bacterial culture to increase accuracy of species identification. MALDI measures protein expression and generates a unique protein 'fingerprint' for each bacterial isolate. This allows characterization of the bacteria beyond 'species', to a sub-species level called 'biotype'. To better understand diagnostic abilities of MALDI, we performed whole genome sequencing (to recover Leukotoxin and MLST) and MALDI biotyping on *Mannheimia spp.* isolates cultured from around Wyoming. Samples were obtained through routine surveillance and disease sampling during the Laramie Peak Die-off in 2020 and 2021. Here we introduce MALDI biotyping and review the strengths and weaknesses of strain-typing methods to help inform respiratory disease management efforts.

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KEY WORDS: bighorn sheep, *Mannheimia spp.*, mass spectrometry (MALDI), multilocus sequence typing (MLST), respiratory disease, Wyoming.

Multilocus Sequence Typing, Leukotoxin Identification, and 16S rDNA Biodiversity Determination of *Mannheimia haemolytica*, *Bibersteinia trehalosi*, *Pasteurella multocida*, and *Mycoplasma ovipneumoniae*. A Single Assay Using Multiplex PCR, Short-Read Sequencing, and Automated Bioinformatics.

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ABSTRACT: Multilocus sequence typing (MLST) characterizes bacteria based on genetic variability in constitutive (housekeeping) genes, and allows comparisons of bacteria beyond the species designation. This approach has been used to trace outbreaks of diseases, and an MLST approach has been used to examine *Mycoplasma ovipneumoniae* (Cassirer et al. 2017) in bighorn sheep. However, bighorn sheep respiratory disease is a polymicrobial concern, and focus on a single pathogen limits diagnostic and management strategies. To create a broader approach to bighorn sheep respiratory diagnostics, we created a single MLST assay to characterize *Mannheimia haemolytica, Bibersteinia trehalosi, Pasteurella multocida, and Mycoplasma ovipneumoniae*. The assay also assesses the *Pasteurellaceae* leukotoxin A gene (*lkt A*), and broadly assesses the bacterial composition of each sample based on 16S rDNA sequences. The assay is based on a three-step approach: 1) Multiplex PCR to probe samples for targets including four to eight housekeeping genes for each species, the *Pasteurellaceae lkt A* gene, and the 16S rDNA gene 2) Next generation sequencing to determine the genetic sequences of each target, and 3) Bioinformatics in the form of automated software to analyze genetic sequences. This assay was originally designed to assess possible transfer of pathogens from domestic to bighorn sheep in the event of a bighorn sheep mortality from respiratory disease. However, the assay could be useful for many applications in bighorn sheep respiratory disease research and management.

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KEY WORDS: *Bibersteinia trehalosi*, bighorn sheep, leukotoxin, *Mannheimia haemolytica*, multilocus sequence typing (MLST), *Mycoplasma ovipneumoniae, Pasteurella multocida.*

Bighorn Sheep Respiratory Disease Surveillance via Animal Behavior and Community Science

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ABSTRACT: Because Bighorn Sheep Respiratory Disease (BHSRD) leads to reduced lamb recruitment, decreased population growth and stability, and even local extinctions in bighorn sheep (*Ovis canadensis*) populations across North America, monitoring this disease is essential to wildlife management. However, physiological surveillance and sampling is logistically and economically challenging, hampering our ability to detect BHSRD incidence and spread. My work aims to circumvent some of the challenges by developing a surveillance program using clinical signs and behavioral sampling to predict infection in bighorn herds. We observed bighorns in four different sites in Montana from June to mid-August; one with no history of BHSRD, one with no die-offs within the past 5 years, one with die-offs within the past 5 years, and one currently undergoing significant lamb mortality. We performed 20-minute focal behavioral sampling, focusing on one lamb or ewe at a time and noting the time lying down (inactive), grazing, walking, standing, playing, and nursing (active), as well as any other signs of compromised health (e.g., nasal discharge, drooping ears, head shaking, or coughing). Here, I grouped behaviors into active and inactive categories and found that inactivity was more prevalent in diseased populations. These results will help determine which behavioral and clinical signs are most useful in detecting BHSRD, making BHRSD monitoring a prime candidate for low-cost, community science-driven programs.

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KEY WORDS: behavioral sampling, bighorn sheep, respiratory disease.

Fascioloides Magna in Free-Ranging Rocky Mountain Bighorn Sheep (*Ovis canadensis*)

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ABSTRACT: From February to May 2021, four non-migratory rams from the Radium-Stoddart bighorn sheep (*Ovis canadensis*; BHS) herd in the Rocky Mountains of south-eastern British Columbia died of infection with the giant liver fluke (*Fascioloides magna*). Affected animals were emaciated, weak and lethargic or were found dead. Gross lesions, histopathology and parasite burdens were consistent with those reported in experimentally infected BHS, domestic sheep and other aberrant hosts. While BHS range does not typically overlap with fluke contaminated aquatic habitats, the change in migratory behavior recently observed in some Radium-Stoddart rams may have exposed the affected animals to *F. magna*. This is the first case series describing hepatobiliary trematodiasis associated with *F. magna* in free-ranging BHS. Based on experimental data and our findings, giant liver fluke is pathogenic and is a threat to the conservation of the Radium-Stoddart BHS herd and other BHS herds in endemic *F. magna* regions.

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KEY WORDS: bighorn sheep, British Columbia, *Fascioloides magna*, giant liver fluke.

Evaluating Ability of Cameras to Accurately Estimate Vital Rates for Desert Bighorn Sheep (*Ovis canadensis nelsoni*)

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ABSTRACT: Researchers and managers use camera traps to monitor desert bighorn sheep (*Ovis canadensis nelsoni*) water guzzler use in southern Nevada. Desert bighorn sheep populations face threat from recurrent disease outbreak and increasing drought regimes. Addressing desert bighorn conservation questions and management action requires accurate occupancy and population modeling. However, the ability of non-randomly positioned trail cameras to accurately estimate bighorn sheep population vital rates remains unclear. Here we paired camera and observer data to estimate camera trap detection probabilities and group size biases from camera to improve their applicability for population vital rate estimation. We conducted our analysis at three scales: describing the probability of capturing a photo of bighorn over the duration of a period when they are present; describing the probability of capturing a photo of newly arriving groups of sheep upon arrival; and describing the bias of group size estimates of demographic groups captured in photos compared to observer counts. Estimates of detection probability and bias were modeled as a function of site, camera type used, group size present, and ambient temperature. The probability of camera traps detecting bighorn over the duration of their presence ranged widely across sites (approximates 0.14-0.45). Detection of new group arrival ranged similarly ranged widely across sites (approximately 0.05, var = 0.85). Group size bias correction demonstrated a low bias across sites and demographic groups (approximately 2.07-10.47). Our results provide managers a way to adjust camera-derived estimates to alert managers to potential changes in desert bighorn vital rates and help prioritize future active monitoring efforts.

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KEY WORDS: bighorn sheep, camera traps, detection probability, vital rates.

Testing the Tools: Montana's Highlands Bighorn Sheep [*Ovis canadensis*] Project

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ABSTRACT: More than a dozen of Montana's bighorn sheep (*Ovis canadensis*) herds have experienced all-age pneumonia die-offs in the past two decades and most have yet to fully recover. Wildlife managers have employed various strategies to help restore these herds such as natural herd re-establishment (hands-off approach), augmentations, and complete herd removal. Using the Highlands bighorn sheep herd in SW Montana, we designed a 5-year study to explore the efficacy of a tool for restoring bighorn sheep herds following a pneumonia outbreak: identification of and subsequent removal of chronic shedders of *Mycoplasma ovipneumoniae* (*M. ovi*). Utilizing the metapopulation structure of the Highlands herd, we will collect two years of baseline information on the five sub-herds that comprise the Highlands metapopulation to 1) monitor disease exposure of individuals and identify chronic shedders, 2) monitor lamb survival, and 3) estimate connectivity of sub-herds. We will then implement two years of a testing and removal of known chronic shedders across all five sub-herds. The efficacy of this treatment will be monitored through year 5. A decrease in prevalence of *M. ovi* shedding and exposure in the sub-herds would indicate success of the management tool. Results of this experiment will add to the growing knowledge of test and removal as a viable tool to manage struggling bighorn sheep herds across Montana and the intermountain West.

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KEYWORDS: Bighorn sheep, chronic shedder, *Mycoplasma ovipneumonia*, *Ovis canadensis, test and removal*

INTRODUCTION

Bighorn sheep herd recovery in Montana (MT) following disease-related die-off events has had mixed success. Currently, Montana Fish, Wildlife and Parks (FWP) is exploring a novel approach to facilitate and expedite herd recovery. In some populations, bighorn sheep augmentations have failed to improve herd performance following all-age pneumonia die-off's. Such is the case in the Highland Mountain area where bighorn sheep experienced a die-off in 1994-95. Historically, bighorn sheep in this area were extirpated in the early 1900's and re-established by a transplant from Sun River in 1967. The population increased to 300-400 animals over the ensuing decades until the 1994-95 die-off reduced the population by 90%. Since then, multiple augmentations from five MT populations (Sun River, Bonner, Sula, Ruby Mountains, Fergus) added 118 sheep to the Highlands herd. The last augmentation occurred in 2015. Despite these efforts, the Highlands population continues to struggle with low population growth.

In the Highlands population and several others in MT, population recovery following an all-age pneumonia event is suspected to be limited by persistent disease. Bighorn sheep populations commonly host respiratory pathogens that may reduce recruitment rates for some time post die-off (Butler et al. 2017, 2018).

Due to testing protocols and interpretations that do not account for uncertainty in pathogen detection, respiratory disease dynamics are poorly understood; however, it is believed to be a polymicrobial disease that is initiated by *Mycoplasma ovipneumoniae* (M.ovi) that permits other bacterial species, such as those in the *Pasteurellaceae* family, to invade the lungs through inhibition of ciliary action (Cassirer et al. 2018). The initial outcome of M.ovi infection is often all-age die-offs resulting in high levels of mortality (Cassirer et al. 2018). These initial die-offs are commonly followed by annual epizootics among juveniles and sporadic pneumonia mortality among adults (Cassirer et al. 2013, Smith et al. 2014). Additionally, environmental and individual factors such as use of mineral licks, nutritional status, social interactions (Manlove et al. 2014), and movement behaviors (Lowrey et al. 2020) may interact with pathogens to influence disease expression. Trace mineral deficiencies may also lead to immunological deficiencies and increase susceptibility to bacterial infections (Flueck et al. 2012, Garrott et al. 2020), as well as physiological stress (Ayotte et al. 2006). Despite these uncertainties in the drivers of respiratory disease, our current focus is on reducing transmission of M.ovi.

Ground observations from 2007-2015 confirmed that the Highlands bighorn sheep population is comprised of five sub-herds (Foothills, LaMarche, Notch Bottom, Red Mountain, Sheep Mountain). Ewes appear to display sub-herd fidelity while rams frequently move between sub-herds; however, there is some overlap in ewe home ranges between at least two of the sub-herds. The bighorn sheep population objective for the Highlands Mountains (Hunting District 340) is a minimum viable population of 125 animals (FWP Conservation Strategy, 2010). The current estimated abundance is approximately 120 animals and has exhibited a stable population for the past several years.

The objective of this project is to evaluate the efficacy of test and removal management actions to increase lamb survival and population performance, and ultimately inform management to recover struggling bighorn sheep populations. In some bighorn sheep populations, removal of chronically infected individuals from herds has been shown to potentially improve population performance (Garwood et al. 2020). However, it can be difficult to identify individuals who are chronically shedding the pathogen because the gregarious nature of bighorn sheep within their ewe-lamb groups makes the likelihood of M.ovi transmission high, resulting multiple individuals being intermittently infected despite not being chronic shedders. The presence of these intermittent shedders makes it difficult to identify chronic shedders in the absence of serial testing. Additionally, given the difficulties in repeat capturing bighorn sheep for disease testing, uncertainty in disease testing efficacy (Butler et al. 2017, Paterson et al. 2020), repeat testing may or may not accurately identify all chronically infected individuals. It also is not currently known if the removal of all chronically shedding individuals is required to affect the desired changes in population performance. Therefore, there is a need to critically evaluate whether the identification and removal of chronic shedders can affect the desired management outcomes.

STUDY AREA

The Highlands Hunting District 340, located just south of Butte, contains approximately 1,141 square miles and includes the Highland Mountains and the northern portion of the East Pioneer Mountains near the town of Melrose. Interstate 15 and the Big Hole River separate the two mountain chains. The district is comprised of shrub-grasslands (sagebrush, mountain mahogany, bluebunch wheatgrass, Idaho fescue), coniferous forests, and agricultural lands. Forty-two percent of the district is in private ownership located primarily at the lower elevations of the district. The majority of private land is in agricultural production, primarily cattle although there are several hobby sheep and goat farms as well.

Approximately 233 square miles of the district (20%) is currently occupied by bighorn sheep during some portion of the year. Sixteen percent of the occupied area is private land and 84% is public lands. Bighorn sheep winter range comprises approximately 188 square miles of this district (16%); 23% is private land and 77% public lands, with the majority of public land being administered by the BLM. Based on past and current telemetry data and recent observations, the majority of the bighorn sheep population winters on public lands.

The vegetation within the occupied bighorn sheep range is predominantly rocky terrain interspersed with sagebrush-grassland, mountain mahogany, and lodgepole-Douglas fir forest. Elevation ranges from 1,460-3,100 meters. Annual precipitation ranges from 20-30 cm at the lowest elevations to 53-79 cm at the upper elevations.

METHODS/FUTURE PLANS

Our overall experimental design was to evaluate the effectiveness of test and removal on lamb survival and population performance in a before-after treatment design. All five sub herds within the Highland Mountains will be monitored for two years prior to management treatments. This monitoring period is required to determine sub-herd disease exposure, chronic shedders (those individuals with 2 or more positive exposures to M.ovi), monitor baseline lamb survival, and identify potential interchange among sub-herds. Management treatments will be implemented in years 3 and 4 of the project and monitored through year 5. This monitoring period is required to determine post-treatment pathogen exposure and lamb survival. At the conclusion of this study, based on results of the treatment, management actions may be continued or modified. If no post-treatment improvement in lamb survival and population performance is observed and disease is confirmed within the treated sub-herds, the sub-herds with persistent disease exposure may be removed.

In all sub-herds, we propose to capture, collect biological samples and GPS collar all ewes, capture sample and GPS collar as many 6-month lambs as possible, and capture, sample and GPS collar up to 20 males per year. Ewes will be outfitted with a vaginal implant transmitter to locate her lamb for neonatal capture and collaring. The data from collared ewes will be used to delineate seasonal ranges, document movements of lamb-ewe groups and identify potential interchange between sub-herds. The data from collared rams will be used to document the extent and types of movements between groups, assuming that rams are the demographic group most likely transmitting pathogens among sub-herds in the metapopulation. Neonatal lambs will be outfitted with GPS or VHF expandable collars for tracking their survival to age 1.

Some captures may be possible with drop netting, ground darting or trapping, and helicopter net-gunning will be used for remaining capture operations. Sampling will include disease testing to screen for pathogen shedding, collection of blood for serology and pregnancy assessment (ewe's only), and a body condition assessment. The pathogen testing protocol will include: 1) collecting blood for serological testing for exposure to M.ovi and a suite of viral pathogens including CE, PI3, BRSV, OPP, IBR, and a trace mineral assessment, 2) collecting pellets to screen for lungworm and intestinal parasites, 3) collecting replicate nasal swabs to test for M.ovi using PCR, and 4) collecting replicate tonsil swabs for aerobic bacterial culture and testing for Leukotoxin A using PCR. Each animal each year will be classified as infected if either the first or the second nasal swab is positive for exposure to *M.ovi*. Given the difficulty of repeatedly capturing and sampling every ewe every year and uncertainty in testing results, conclusive evidence for differences in pathogen communities between sub-herds and identifying chronically infected animals may be difficult or impossible to evaluate. Nonetheless, we plan to utilize replicate swabs and a combination of aerial and ground capture efforts to maximize sample sizes and make sampling as rigorous as possible. Whole blood will also be fixed on a gene card and the eartag punch saved for genetic archiving.

Animals with at least 2 repeated positive M.ovi PCR tests will be classified as chronically infected and animals with a single positive M.ovi test will be considered infected. In this management experiment, we plan to test individuals 1-2 times per year and remove any individuals that are chronically shedding M. ovi. We will euthanize any chronically shedding bighorn sheep during capture. Any chronic shedders identified post release through conventional pathogen testing methodologies will be radio tracked and euthanized with a gunshot. All heads will be collected and examined for nasal tumors.

We will monitor lamb survival using two approaches: first, we will estimate the number of lambs produced, the number surviving until the end of summer and the number surviving until the end of spring using a combination of ground and aerial counts and classifications; and second, we will estimate lamb survival directly based on a sampling of marked individuals. We will capture lambs as neonates and outfit each with a VHF or GPS collar that remotely monitors live/dead status. Lambs will be monitored for survival and observed for signs of pneumonia infection 3-4 times per week. Causes of mortality will be investigated. During each observation, the group composition and size will be recorded. The presence of a marked ewe's live lamb will be determined based on nursing, body contact or other association patterns (see Cassirer et al. 2013), or the lamb's collar. This information will be used to document the interchange and spatial patterns of lamb-ewe groups during the lamb rearing period, estimate annual lamb survival for each sub-herd, and document the presence of disease and/or infection.

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Montana's Sun River Bighorn Sheep (*Ovis canadensis*), Decimation to Restoration and Back Again…Ugh!

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ABSTRACT: The Sun River bighorn sheep (*Ovis canadensis*) herd has consistently been one of the largest and most robust native herds within Montana. Early European settlement records indicate bighorn sheep presence in the upper Sun River drainage area as early as 1866, although it is reasonable to assume that bighorn sheep have inhabited the upper Sun River drainage for a period well before then. By the early part of the 20th century, bighorn sheep numbers in this area were dramatically reduced. The causes most often cited were range competition from livestock and other big game animals, contact with domestic sheep (subsequent contraction of disease), and subsistence hunting. During the 1930s, bighorn sheep recovery began in the Sun River area due to the reversal of the previously noted conflicts. There have been five recorded die-off events for the Sun River herd (1924-25, 1927, 1936, 1983-84, and 2010-11). Post die-off events, herd reestablishment has been due to natural production, survivorship and recruitment. Beginning in spring 2010, a disease outbreak in Sun River sheep began (all age/gender die-off). This event arguably has had the largest population level impact on sheep in this area in the last century, reducing population levels over the next several years by as much as 70% coinciding with observed single digit lamb:ewe ratios. Pre- and post-die-off disease monitoring data portray somewhat unremarkable variability in pathogen presence, despite confirmed widespread infection of polymicrobial bacterial pneumonia including the presence of *Mycoplasma ovipneumoniae* during the die-off period. Taking a relatively hands off management approach, current (spring 2023) population surveys place Sun River sheep at over 400 animals, the highest observed number in a decade, with a calculated 38 lambs:100 ewes. Given the status and gradual, natural recovery of sheep to date, the hands-off management approach provides one example of the value of understanding all facets of herd history and allowing time and opportunity for natural herd recovery before enacting potential large scale hands-on management efforts.

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KEY WORDS: *Bibersteinia trehalose*, bighorn sheep, disease, die-off, *Mannheimia, Mycoplasma ovipneumoniae (*Movi*), Pasteurella*, Sun River

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INTRODUCTION

The first recorded European explorations of the Sun River country were by Lewis and Clark in June of 1805, however, no bighorn sheep observations were noted. Rocky Mountain bighorn sheep presence in the upper Sun River drainage was first reported in 1866 (Couey 1950). Earlier reports exist in other locations within the Rocky Mountains, and it is reasonable to assume that bighorn sheep presence in the Sun River country has been persistent for at least the last two hundred years. Like other wild sheep populations, around the turn of the 20th century sheep numbers in this area declined due to range competition from livestock and other big game (primarily elk), contact with domestic sheep (and subsequent disease), and subsistence hunting (Picton 1975). However, bighorn sheep populations did not suffer complete eradication due to the natural topography of the area, natural bighorn sheep distribution across the landscape, and the ability for sheep to separate themselves from other livestock and big game concentrations. Unverified reports of good numbers of sheep were noted in 1908 and 1910 in two different locations within the Sun River area (Couey 1950).

By the 1930s, sheep numbers in the area were recovering and demonstrated overall general population stability for the next seven decades. By 1940, populations had recovered to the point of utilizing Sun River area sheep as a source population to help establish, reestablish, or augment other bighorn sheep populations in Montana. The first of many successful translocation efforts in this area was accomplished in 1942 with the last translocation event taking place in 2009 (Carlsen et al. 2010). Total sheep translocated from the Sun River area during the seven-decade period equates to nearly 1,200 individuals received in over 30 different locations within and outside the boarders of Montana. During this same period, hunting opportunity was also maintained as a high management priority with approximately 1,800 ram (either-sex) and 1,200 adult ewe licenses offered. Long-term average success rates for ram and adult ewe licenses near 90% and 60%, respectively.

However, despite research and management efforts to manage sheep populations within objective range to sustain herd health, beginning in late spring and summer seasons of 2010, clinical signs of sick and/or dead sheep began to occur, resulting in widespread population reduction in the proceeding years throughout the Sun River sheep range. The impacts of the 2010/2011 disease outbreak have had extensive implications and is arguably had the most significant influence on overall herd health and population performance in at least the last century. Understanding general sheep herd history and past and current management strategies related to current circumstances and disease prevalence has demonstrated its importance to making informed management decisions geared towards population recovery.

STUDY AREA

The upper Sun River drainage and surrounding occupied sheep habitat is in west central Montana along the eastern edge of the Rocky Mountains known as the Sawtooth Range (Figure 1). The area lies approximately 60 miles south of Glacier National Park and on the east edge of the Bob Marshall Wilderness. This area is comprised of Montana Fish, Wildlife & Parks (FWP) administrative bighorn sheep hunting districts (HD) 421, 422, 423 and 424. Together, these HDs represent over 2,900 km² of land with approximately 855 km² (30%) occupied by bighorn sheep during at least some portion of the year. Over 90% of the occupied sheep habitat is public land (U.S. Forest Service, Bureau of Land Management, or Montana Fish, Wildlife and Parks). Although less than 10% of the existing occupied sheep habitat is private land, these lands are important, especially during the late fall through early spring season.

Figure 1. General location and distribution of the Sun River Bighorn Sheep herd within Montana.

METHODS

This manuscript focuses primarily on broad management information and approaches with some research input. Therefore, methods briefly summarized pertain to annual bighorn sheep survey monitoring work as well as disease surveillance as part of management and statewide research efforts.

Population Surveillance

Annual bighorn sheep surveys are completed in spring, mid-summer and late fall. Depending on the area, accessibility and time of year, survey methods include aerial based efforts (A-Star, JetRanger or Hughes 500 helicopters or Piper PA-18 Super Cub fixed wing aircraft), four-wheel drive truck, foot (hiking), and horseback surveys. Optics used during survey work such as spotting scopes and binoculars, handheld GPS units, telemetry, and survey data sheets for consistent repeatability are considered standard equipment.

Spring surveys are completed via a variety of survey methods previously described and are focused on post winter survivorship and obtaining accurate classifications of individuals to portray lamb:ewe (yearling recruitment) and ram:ewe ratios as well as overall population numbers. Summer surveys are completed via helicopter with the primary focus on obtaining early season lamb production counts and subsequent lamb:ewe ratios. Late fall/early winter surveys utilize a variety of survey techniques and again, focus on obtaining representative lamb:ewe and ram:ewe ratios, as well as overall numbers. Fall surveys also portray overall herd performance prior to the primary winter period.

Disease Surveillance

Given lack of health related to issues for bighorn sheep in this area, focused disease surveillance efforts prior to 2010 were only completed as part of translocation work. Standard samples collected for disease testing during translocation work included general body condition scores, serum (blood) for viral testing, pharyngeal tonsil and nasal swabs for diagnostic bacterial culture testing, and fecal samples correlated with parasitology testing. Beginning in 2011 and due to widespread disease concerns, translocation work ceased within the study area and instead, focused more on opportunistic disease surveillance efforts. This included obtaining the same samples previously described for testing via ground darting, postmortem necropsies on viable carcasses found afield, and hunter collected samples upon harvesting a sheep. In 2013, FWP and Montana State University (MSU) began a multiyear statewide research program designed to assess factors driving bighorn sheep population dynamics across Montana (Garrott et al. 2021). Through this project, standardized sampling and testing methods were developed and refined. This included collection of many of the same or similar samples, however, also included improved methods to better detect pathogens. Culture- and PCR-based pathogen diagnostic tests were utilized upon collection of multiple tonsil and nasal swabs to test for a variety of pathogens to include *Pasteurellaceae species*, *Mycoplasma ovipneumoniae* (Movi), *Mannheimia spp*. and *Bibersteinia trehalose*. Exposure of sampled animals to Movi was also assessed using serum from blood collected. Other non-disease focused data collected during the Garrott et al. project included gender, age (estimated using incisor eruption patterns) (Hemming 1969), and lactation status of adult females. Ultrasonography was used to measure subcutaneous rump fat thickness of adult females and body condition was also assessed using skeletal palpation methods. Additionally, weight and hind foot length (Zannése et al. 2006, Garel et al. 2010) were measured for all adult females. For further information related to sample collections, refer the Garrott et al. (2021) final report.

RESULTS

Population Surveillance

Prior to 2010 and within the cumulative FWP trend survey areas, long-term average observed (minimum) number of sheep during annual surveys (spring season) tally just over 500 individuals (n=514). It is noteworthy that given the survey types utilized correlated with seasonal weather patterns, observability of sheep is variable from season to season or year to year, at times reflecting large fluctuations in sheep observations. April (spring) 2010 provided ideal survey conditions and subsequently population survey data produced not less than 933 bighorn sheep within established upper Sun River trend survey areas with a calculated lamb:ewe:ram ratio of 28:100:61 (Figure 2). In June, the first report of a clinically compromised sheep (ram) was observed on what would be classified as primarily winter range habitat and during summer 2010, limited reports of sick and/or dead sheep were reported. A late summer 2010 helicopter survey was completed as part of other big game survey work and of 51 sheep observed, no lambs were classified. By late fall 2010, the overall population declined by approximately 39% (n=568 observed sheep) and a lamb:ewe:ram ratio of 5:100:62. Approximately 4 months later, spring 2011 surveys produced further reduced numbers with 43% fewer sheep (n=535) than what was observed one year previous and lamb:ewe:ram ratios of 5:100:63 (Figure 2). Of the 535 sheep observed in spring 2011, only 13 lambs were classified. Spring 2018 survey observations hit a low point with population observations reduced by 71% (n=266 observed sheep), albeit with improved lamb recruitment at 30 lambs:100 ewes (Figure 2).

In general, the die-off impacted both males and females and across all ages. However, since 2018, overall populations have improved with

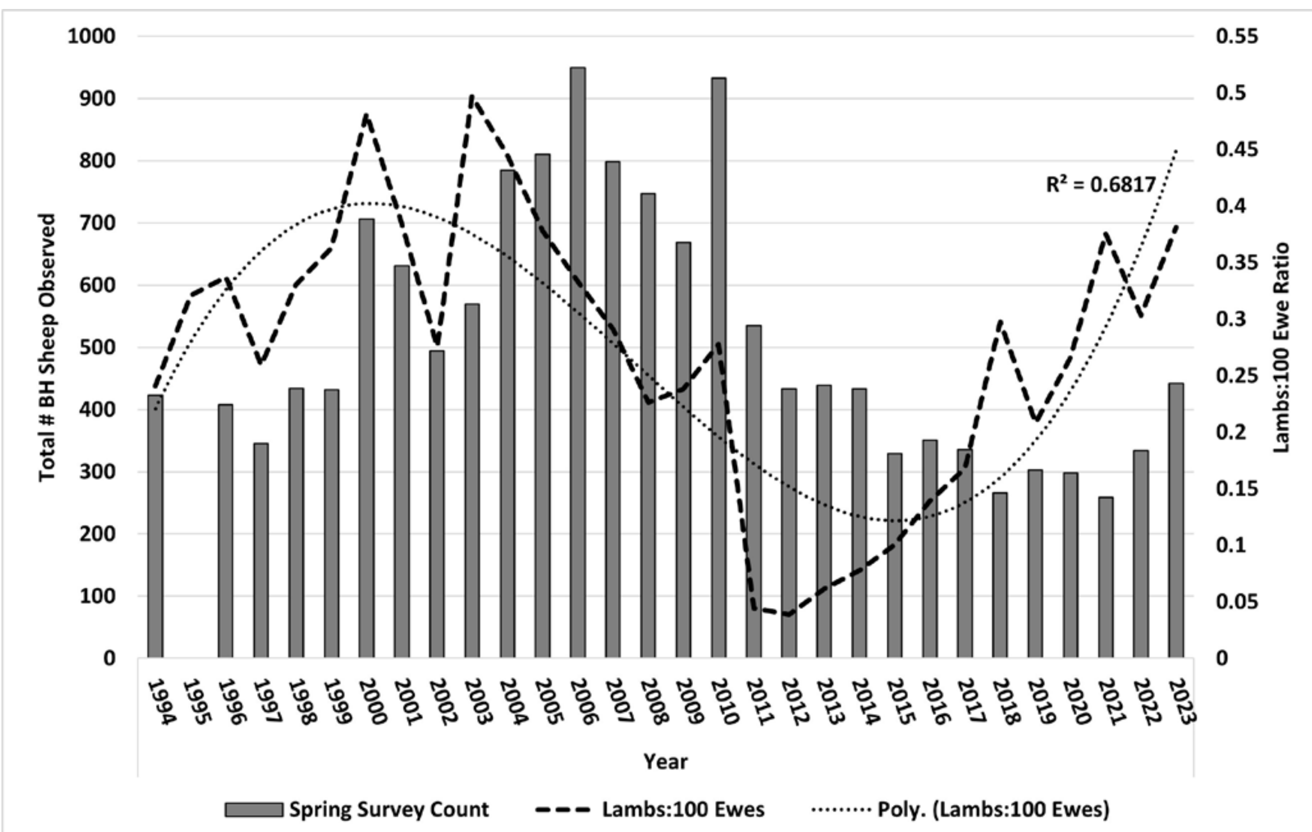

Figure 2. 30-year comparison (1994-2023) of total observed Sun River bighorn sheep and calculated lambs:100 ewes during annual spring surveys. Lamb:ewe ratios this time of year are focused on those lambs born the previous year (nearing their first birthday – recruitment) and is prior to the parturition period.

spring 2023 observations the highest in a decade (n=442) along with near long-term average (prior to the 2010/2011 die-off) lamb recruitment at 38 lambs:100 ewes (Figure 2). Due to the significant reduction in lamb survivorship, ram age structure and ram:ewe ratios also declined but with more recent improvement in lamb survivorship, ram numbers improved with a relatively strong cohort of two- to five-year-old rams in the population.

Disease Surveillance

Over a three-year period (2007-2009), and as part of efforts to help reduce sheep numbers closer to objective levels (in addition to adult ewe licenses offered), a total of 189 sheep (155 ewes, 20 rams, 12 lambs) were translocated from the upper Sun River area to other locales in MT and other states. As is routine with most translocation related work, disease sampling was completed during sheep processing prior to being placed in trailers for transport (Table 1). Culture positive results for individuals with general higher to lower prevalence rates included *B. trehalose*, *M. haemolytica* and *P. multocida*, in that order (Table 1). Parasites such as Coccidia, Lungworm and other intestinal parasites were detected with variable load levels (Table 1). Movi was detected using enzyme-linked immunoassay (ELISA) testing in which approximately 11% tested positive (Table 1).

In March 2011, and in response to the ongoing die-off event, limited ground darting effort was completed to sample sheep and test for pertinent pathogen prevalence. Seven individuals (5 ewes and 2 rams) were targeted during ground darting effort and similarly sampled for various pathogens. Five individuals were culture positive for *B. trehalosi* and one individual for *P. multocida*. Parasite prevalence was detected as well with four of six sheep sampled being positive for Coccidia and

Table 1. Pathogen and parasite detection from three time periods based on serology and culture based diagnostic testing as well as other sampling measures. Pathogens are noted as the actual number individuals tested (+ positive, - negative, etc.) and percentages are based on the number of samples submitted for testing.

CULTURE-BASED POSITIVE DIAGNOSTIC RESULTS									
		***Bibersteinia trehalosi* (%)**	***Mannheimia haemolytica* (%)**	***Pasteurella multocida* (%)**	***Mannheimia spp.* (%)**	***Pasteurella spp.* (%)**			
2007-2009 Translocation Samples		158 (84%)	55 (29%)	3 (2%)					
2011 Ground Dart Samples		5 (71%)		1 (14%)					
2014-2022 Management / Research Samples		40 (34%)	2 (2%)	18 (15%)	5 (4%)	5 (4%)			
DETECTION OF *Mycoplasma ovipneumoniae*									
	ELISA + (%)	**ELISA - (%)**	**ELISA suspect (%)**	**ELISA Indeterminate (%)**	**ELISA N/A (%)**	**PCR + (%)**	**PCR - (%)**	**Suspect (%)**	**PCR N/A (%)**
2007-2009 Translocation Samples	11 (6%)	89 (47%)	1 (<1%)						
2011 Ground Dart Samples	2 (29%)	5 (71%)				3 (43%)	3 (43%)		1 (14%)
2014-2022 Management / Research Samples	23 (19%)	13 (11%)		1 (<1%)	34 (29%)	15 (13%)	94 (79%)	5 (4%)	
***Pasteurella* Leukotoxin lktA**									
			PCR + (%)	**PCR - (%)**					
2014-2022 Management / Research Samples			3 (7%)	38 (93%)					
PARASITOLOGY									
		Coccidia		**Intenstinal parasites**		**Lungworm**			
2007-2009 Translocation Samples		Yes / Widspread (light parasite loads)		Yes / Widespread (light parasite loads)		Yes / Widespread (light parasite loads)			
2011 Ground Dart Samples		Yes (4 of 6) w/light parasite loads		Yes (4 of 6) w/light parasite loads		Yes (3 of 6) w/light parasite loads			
2014-2022 Management / Research Samples		Yes (16 of 20) variable w/light parasite loads		Yes (15 of 20) variable w/light parasite loads		Yes (20 of 20) w/light parasite loads			

intestinal parasites, albeit with light parasite loads. Lungworm was detected in three of six individuals, also with light parasite loads. Movi was tested for via both ELISA and polymerase chain reaction (PCR) tests. Two and three of the seven individuals sampled were positive for Movi via ELISA and PCR testing, respectively.

Lastly, from 2014 through 2022, additional disease sampling was completed as part of formal statewide research (Garrott et al., 2021), hunter harvest samples, field necropsies of viable carcasses, and concerted effort to redeploy GPS collars from research/monitoring mortalities to maximize collar life span. This equates to 119 individuals (60 ewes, 54 rams and 5 lambs). Based on culture results, *B. trehalosi* was detected in 40 individuals, *Mannheimia spp*. in 18 individuals and only a handful of positive detections for *M. haemolytica*, *P. multocida* and *Pasteurella spp*. (Table 1). Consistent and variable loads of Coccidia, Intestinal parasites and lungworm were detected among most individuals that were sampled in this regard (Table 1). Using ELISA testing methods, 72 individuals were sampled for Movi with 23 testing positive, however it is important to note 34 individuals had unavailable results. Using PCR testing methods, 114 individuals were tested, portraying 15 positive individuals and 5 that were defined as suspect (all others negative). *Pasteurella* Leukotoxin lktA was also tested for via PCR for 41 individuals. Three individuals were positive for P. Leukotoxin lktA.

In summary, over 300 sheep were sampled over a 16-year period providing a relatively strong set of pre- and post- disease event pathogen data. Sheep portrayed a wide variety of test results across multiple pathogens that allows for unique analysis with respect to pre- and post- population performance monitoring.

DISCUSSION

Before 2010, there have been four bighorn sheep die-offs recorded in this area in the last century. The first die-off occurred during 1924-25 with an estimated population loss of 70%. Forage competition with other big game (elk) and livestock was thought to be a major contributing factor. Other smaller die-offs were recorded in 1927 and 1936, but the magnitude is unknown. Field diagnosis of some of the dead sheep in the 1924-25 and 1927 die-offs indicated pneumonia as the cause of death (Marsh 1938). In 1983-84, an estimated loss of 30-50% of the population occurred. Estimates vary due to certain areas within the greater Sun River region had higher losses than others. The latter die-off was primarily caused by bronchophneumonia complicated by pulmonary nematodiasis. The true origin of the 1983-84 disease outbreak is unknown, although a plausible scenario consists of a disease outbreak that started in the spring of 1983 at Crowsnest Pass-Waterton Lakes National Park, Canada, worked its way south through Glacier National Park and eventually down the eastern flank of the Rocky Mountain Front and the Sun River region (Montana Fish, Wildlife & Parks 1984). Persistence of non-native pathogens in sheep in the Sun River area is assumed to be endemic to the area for decades. Except for a small transplant in 1999 in the northeastern range of bighorn distribution, all population growth post die-off has been the result of natural production, recruitment, and immigration.

Like the 1983/84 die-off, origins of the 2010/11 die-off are unknown. Although translocation captures completed in 2007-2009 period portrayed some level of pathogen presence that is known to cause die-off events, no observations of visibly unhealthy sheep were noted. Observations of sheep during winter (December) and spring (April) 2010 surveys also portrayed healthy individuals with no visible signs of sickness. Winter and early spring habitat conditions were considered normal for this time of year in this area, assumed to not be an added stress related event providing opportunity for disease expression. During approximately this same period, other wide-spread bighorn sheep die-off events occurred in

Western Montana (Dickson 2011), although are believed to be independent of the Sun River die-off given geographic distances and topographic variability between sheep ranges. One possible scenario that has been discussed is potential implications of translocated mountain goats into a portion of sheep habitat in the northern end of Sun River sheep distribution. In 2008 and 2009, a total of 25 mountain goats were trapped and translocated from two different sources within central and southcentral Montana. Interestingly, these two source herds were also areas that were initially established using translocated mountain goats from the Sun River area decades previous. Given current knowledge of potential pathogen mixing implications between wild sheep and goats, it is plausible that during the 2008/2009 period such interactions could have taken place and taken time to spread into a widespread disease event with existing local bighorn sheep. Unfortunately, disease results from the mountain goat transplants are limited and does not provide good conclusive perspective into this potential commingling scenario.

In reviewing pre- and post-die-off bighorn sheep disease results definitive conclusions related to potential novel pathogen introduction into the area is difficult. Culture-, ELISA- and PCR-based diagnostic test results gives no indication of novel pathogen arrival into the area, although variable prevalence rates. However, given the refinement of testing abilities over time, pathogens such as Movi, to include strain typing abilities, could allow for improved detection rates that were not available or at least not widely used prior to the most recent die-off event, hence, compromising making strong inferences between pre- and post- disease data. Nonetheless, disease data do show pertinent pathogens, such as Movi, present within Sun River sheep providing confirmation for the likely primary agent(s) causing widespread population declines during the decade succeeding 2010.

Despite an approximate 70% decline in upper Sun River area sheep populations, decisions made to heavily monitor, but not directly attempt to mitigate ongoing disease presence post die-off was not an easy decision to make and at times, was met with considerable consternation. Given the history of a general hands-off disease management approach and subsequent consistent recovery of bighorn sheep in this native herd, allowing time for processes to naturally play out was the ideal path forward for at least the immediate interim. Although it appears sheep are gradually making headway towards eventual recovery in this area, certain areas (sub-herds) are faring better than others, perhaps due to low level presence of pathogens persisting in some areas. Of course, with smaller herd sizes, additive impacts of potential habitat limitations (short- or long-term) predation, and annual weather events must also be considered. Test and removal management strategies has been considered, but at least for the interim, not something being pursued given generally herd stability, albeit at low levels in places, but improving lamb recruitment. Additionally, within range transplants (using source sheep from more productive sub-herds) is also being considered as one means to help bolster those sub-herds that appear to be slower to recover. The assumption being that little concern, if any, should be had with respect to introduction of novel pathogens if sheep were moved given assumed widespread distribution of the same pathogens within Sun River sheep range, and distances are far enough that movement of translocated sheep would not be all for not as/if they returned to their accustomed home range. However, as has been the case, continued monitoring is ongoing and such data will help make more informed decisions with respect to any such direct management approaches for upper Sun River sheep.

Ultimately, management of bighorn sheep in the upper Sun River drainage has a storied history within the borders of Montana. Although this latest chapter for this population of bighorn sheep has been a difficult road, recovering and maintaining this population as one of Montana's premier native sheep herds remains a high priority for not only the benefit of the natural resources of this area, but for future generations of Montana's to appreciate and enjoy.

ACKNOWLEDGMENTS

The information gathered and summarized in this manuscript is presented in recognition of all the good biologists, conservationists, researchers, graduate students and sportsmen and women that have worked and lived in the Sun River Country. Persistence of bighorn sheep in this area is a testament to their work and true appreciation for wild sheep and emphasizes the desire to continue to maintain a healthy and robust population of bighorn sheep in the Sun River area for generations to come.

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Whiskey Mountain Bighorn Sheep – Pullin' on a Management Lever

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ABSTRACT: The Whiskey Mountain herd may arguably be one of the most familiar, if not famous, populations of bighorn sheep. At one time, not too long ago, this herd was thought to be the largest Rocky Mountain bighorn sheep population in North America, but not anymore. A central issue related to the long-term decline in the Whiskey Mountain bighorn sheep population is respiratory disease. The herd experienced an all-age die-off during the winter of 1990/1991, during which 124 bighorn sheep mortalities were attributed directly to pneumonia and the total number of mortalities was estimated at 450 bighorn sheep. Thereafter, this herd has declined from ~2,000 animals in the late 1980s to ~400 today. In the spring of 2019, Wyoming Game and Fish Department (WGFD), the U.S. Fish and Wildlife Service, and the Haub School at the University of Wyoming initiated an intensive lamb mortality study to better understand the circumstances underpinning low lamb recruitment. This study involves twice-a-year testing of adult ewes for respiratory pathogens and collaring of neonatal lambs to determine cause-specific mortality. Several ewes in this population were identified as chronic carriers of *Mycoplasma ovipneumoniae*, a finding that has been associated with low lamb recruitment in other jurisdictions. Nearly all of the lambs collared during this effort died during their first 6-8 months of life, and roughly half of the collared lamb mortalities were attributable to pneumonia. Based on these findings, WGFD, the Wind River Reservation's Tribal Game and Fish, and the Haub School recently implemented "test and remove" in the Red Creek sub-herd of this population. In March of 2022, five ewes identified as chronic carriers of *M. ovipneumoniae* were removed from the Red Creek sub-herd. Post-mortem examination indicated that all were pneumonic and three had paranasal sinus tumors. Test and remove in this sub-herd will continue with increased intensity over the next several years in concert with continued monitoring of seasonal nutritional condition, pathogen prevalence, and survival of adult females and lambs. It is hoped that pulling on the "test and remove" management lever yields results similar to other jurisdictions' successes with increased lamb survival and eventual population recovery.

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KEY WORDS: Rocky Mountain bighorn sheep, respiratory disease, chronic carrier, pneumonia, *Mycoplasma ovipneumoniae,* test and remove.

Behavioral Responses of Bighorn Sheep Following a Large-Scale Wildfire

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ABSTRACT: Rapid global climate change is expected to increase the frequency and severity of major disturbance events. Resilience of species to such changes will depend upon their ability to adjust behavior in response to changes in resource availability. We explored behavioral responses of female bighorn sheep (*Ovis canadensis*) to the Lick Creek Fire in southeastern Washington, a high-intensity wildfire that burned ~80,000 acres from July 7–10, 2021. We predicted that bighorn sheep would be displaced by the fire and would alter movement and space-use patterns in response to the drastic short-term reduction in forage availability. We used GPS data from 18 bighorn ewes to quantify patterns of home-range size and fidelity, movement, and habitat selection during the 25 days before versus 25 days immediately after the fire. Despite a dramatic reduction in forage availability post-fire, bighorn sheep were extremely faithful to their pre-fire home ranges. However, we observed shifts in movement patterns post-fire that ostensibly reflected depletion of forage resources. Although bighorn sheep selected areas closer to escape terrain before and after the fire, they were more likely to venture farther from escape terrain to access forage (indexed by NDVI) after the fire. Moreover, sheep selected for high NDVI after the fire, whereas they avoided areas of high NDVI before the fire. These results suggest that bighorn sheep faced a tradeoff between escape terrain and forage pre-fire, but that either (1) the magnitude of that tradeoff attenuated after the fire, or (2) the nature of the tradeoff was altered by the fire, forcing bighorn sheep to use areas farther from escape terrain to find food. Our results also demonstrate that responses of large herbivores like bighorn sheep to disturbance are complex and may simultaneously be plastic in one dimension (e.g., movement patterns) and less flexible in another (e.g., home-range fidelity).

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KEY WORDS: bighorn sheep, climate effects, habitat selection, Washington, wildfire.

Heterogeneity in Risk-Sensitive Allocation of Somatic Reserves in Bighorn Sheep

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ABSTRACT: Patterns of food quality and availability, when combined with energetic demands in seasonal environments, shape resource acquisition and allocation by animals and holds consequences for life-history strategies. Long-lived species with extensive maternal care, regulation of somatic reserves can occur in a risk-sensitive manner, wherein resources are preferentially allocated to support survival at the cost of investment in reproduction. We investigated how Rocky Mountain bighorn sheep (*Ovis canadensis*), an alpine mammal in a highly seasonal environment, allocate somatic reserves (i.e., energy and protein) across seasons. We hypothesized that, in accordance with the risk-sensitive resource allocation hypothesis, accretion and catabolism of somatic reserves would be regulated relative to pre-season nutritional state, reproductive state, and vary among populations in accordance with local environmental conditions. We monitored seasonal changes of percent ingesta-free body fat (IFBFat) and ingesta-free, fat-free body mass (IFFFBMass) in three populations of bighorn sheep in northwest Wyoming between 2015 and 2019 through repeated captures of female sheep in December and March of each year in a longitudinal study design. Allocation of somatic reserves was risk sensitive and varied relative to the amount of somatic reserves an animal had at the beginning of the season. Regulation of fat reserves was sensitive to reproductive state and differed by population, particularly over the summer. In one population with low rates of recruitment, sheep that recruited offspring lost fat over the summer in contrast to the other two populations where sheep that recruited gained fat. And yet, all populations exhibited similar changes in fat catabolism and risk sensitivity over winter. Deviations in magnitude of risk sensitivity across seasons may be indicative of sufficiency in seasonal ranges to meet energetic demands of survival and reproduction. Risk sensitive allocation of resources was pervasive suggesting nutritional underpinnings are foundational to behavior, vital rates, and ultimately, population dynamics. For species living in alpine environments, risk-sensitive resource allocation may be essential to support reproduction and survival.

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KEY WORDS: Rocky Mountain bighorn sheep, body fat, body mass, energetic demands, Wyoming.

The Little Belt Mountains Wild Sheep Restoration Effort

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ABSTRACT: Montana's Bighorn Sheep Conservation Strategy, published in 2010, calls for Montana Fish, Wildlife & Parks (MFWP) to establish "new viable and huntable populations [of bighorn sheep]." While numerous augmentations of existing sheep populations have occurred across the state, no new herds had been established since the Strategy's adoption. Die-offs within other Montana herds and subsequent population declines, coupled with the high resource and economic value of bighorn sheep, have increased the need to establish and promote healthy bighorn populations in Montana. Several habitat models predict suitable bighorn habitat in the Little Belt Mountains, and bighorn sheep were historically present there. During the last decade a few bighorn sheep have naturally returned to the Little Belts, but a viable population has failed to become established on its own. In preparation for a reintroduction effort, MFWP developed partnerships with numerous organizations, local landowners, and the Montana Woolgrower's Association to develop support for this project. In December 2020, 49 bighorn sheep were captured from the Missouri River Breaks sheep herd and released into the Little Belts, and coupled with the Tendoys reintroduction, marked the first wild sheep restoration effort to occur in Montana in over 20 years. This reintroduction was supplemented with an additional 33 bighorn sheep in December 2021. All 82 sheep were fitted with GPS collars to collect locations every 13 hours, while providing mortality notifications as well as a geo-fence to help prevent comingling with domestic sheep. Throughout spring 2021, we conducted extensive monitoring to determine lamb production and survival. Seventy percent of the surviving ewes produced lambs in 2021. To date, 27 ewes have died, mainly due to lion predation. Ewes seem to be more susceptible to mortality during their initial year of release; 6 of the 7 ewe mortalities this winter were from the December 2021 cohort. New RSF habitat models (Lowrey et al. 2021) were highly predictive of actual bighorn sheep habitat selection during both winter and summer. We will continue to monitor bighorn sheep survival, production, and habitat use throughout the coming years and incorporate the Little Belts project into larger statewide research and reintroduction efforts.

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KEY WORDS: bighorn sheep, habitat selection, lamb survival, Montana, reintroduction

Wildfire Recovery To Provide Optimal Habitat For Bighorn Sheep In The Douglas Creek Bighorn Sheep Herd

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ABSTRACT: In fall 2020, the Mullen Wildfire burned 176,000 acres in the southern half of the Snowy Range, 30 miles west of Laramie, Wyoming. Burned lands were dominated by lodgepole pine, which had succumbed to a mountain pine beetle epidemic over 20 years ago, and provided fuel loading for large scale wildfire events. Pre-wildfire, bighorn sheep within the Douglas Creek herd were only found in small portions of their historic ranges where open escape terrain could be found. Wildlife managers had identified conifer encroachment as a limiting factor for bighorns in this herd for the last 40 years. High proportions of the Mullen Wildfire scar were categorized as "High Burn Severity", and managers quickly grew concerned post-wildfire about the threat of invasive vegetative species pioneering into burned areas. Through extensive vegetation monitoring and modeling efforts, 10% of the burn scar was deemed to be at medium to high risk of cheatgrass invasion. The Medicine Bow-Routt National Forest and the Wyoming Game and Fish Department secured over $1 million in grant funding to complete aerial herbicide (Rejuvra®) applications in 2021 and 2022, enough to treat over 14,000 acres. Importantly, the Medicine Bow-Routt National Forest was able to gain clearances for one time treatments within the Platte River and Savage Run Wilderness Areas. Intensive vegetative monitoring plots were established, and will continue to be monitored to determine the effectiveness of treatments, as well as when and where re-treatments may be needed in future years. Nine bighorn ewes within the Douglas Creek herd were captured and fitted with Global Positioning System collars in 2019 (prior to the Mullen Wildfire), and 14 bighorn ewes captured and collared in 2022, including five individuals from the pre-wildfire sample, allowing for an evaluation of habitat use and movements pre- and post-wildfire. Already, bighorns are foraying into previously unoccupied areas recently made available by the Mullen Wildfire. It will be valuable to track the continued response of this bighorn sheep herd following the type of habitat altering event that has been desperately needed for decades.

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KEY WORDS: bighorn sheep, pre and post-fire habitat use, vegetation monitoring, wildfire, Wyoming.

Effects of Helicopter Net-Gunning on Survival of Bighorn Sheep

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ABSTRACT: Wildlife capture, and the data collection associated with it, has led to major advancements in ecology that are integral to decision making pertaining to wildlife conservation. Capturing wildlife, however, can cause lethal and non-lethal risks to animals. Understanding the factors that contribute to the level of risk involved in wildlife capture is therefore critical for the development and implementation of the safest and most effective methodologies. We used data from 736 animal captures of 389 individuals for two subspecies of female bighorn sheep (*Ovis canadensis canadensis* and *O. c. sierrae*) in Wyoming and California, USA, 2002–2020 to evaluate the degree and extent of time that capture via helicopter net-gunning affects survival. We compared pre- and post-capture survival during a 10-week window centered on a capture event, as well as post-capture survival between captured animals and animals that were monitored but not captured during the 10-week window. Additionally, we evaluated the effects of handling techniques (number of times captured, season of capture event, handling time, chase time, and body temperature) and biological factors (age and nutritional condition) on probability of capture mortality. Mean daily survival was 0.9992 during a 5-week pre-capture window, dropped to 0.9864 on the day of capture, and rebounded within 3 days of capture to pre-capture levels and that of sheep that were not captured. Overall, direct mortality resulting from capture was 1.36%, with 0.54% mortality occurring within the 3 days following a capture event for a total of 1.90% capture-related mortality. The only handling and biological metrics that influenced the probability of capture mortality were rectal temperature and nutritional condition; both high initial rectal temperatures and poor body condition were associated with increased risk of mortality in the days following capture. Overall, helicopter net-gunning imposed low and short-term risk to survival of female bighorn sheep. To reduce bias in survival estimates we recommend using a 3-day censorship window for post-capture mortalities as opposed to the common practice of a 2–5-week censor window. Helicopter net-gunning, including annual or seasonal recaptures, remains an effective and comparatively safe technique for capture and associated data collection of bighorn sheep.

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KEY WORDS: California, capture-related mortality, helicopter net-gunning, Rocky Mountain bighorn sheep, Wyoming.

Hornography: Photogrammetry and 2D Measurement Can Be Used to Assess Bighorn Sheep (*Ovis canadensis*) Horn Morphology

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ABSTRACT: As a result of a review of arguments addressing the selection and counterselection of secondary sexually selected traits in Rocky Mountain bighorn sheep (*Ovis canadensis*). We have identified some gaps in our knowledge which complicate our ability to study and comment on the matter. The primary issue is that horn measurements are routinely completed for deceased bighorn sheep; either individuals that have been legally hunted, found dead or confiscated. Additionally, measurements are done at time of capture, which tends to occur during the first few years of life. Thus, data sets compiled using this approach are inherently biased towards larger males, as those are the ones that are targeted later in life. Therefore, as not all sheep are found dead, the measurements based on deceased individuals and juveniles do not necessarily represent the living population. Given, the bias in existing datasets, we decided to investigate whether the size and annual growth of bighorn ram horns could be accurately measured using non-invasive photographic techniques, specifically using photogrammetry and 2D measurements on photographs from live animals. Our second goal was to use photogrammetry to build 3D models that could provide scaled depictions of a male's horn size and shape. To test the accuracy of the 2D measurement technique, we used photos of sheep with known manual measurements and compared the digital and manual measurements. To test the accuracy of the photogrammetry technique, we used the method on the horn of a deceased individual. A scaled 3D model was produced with annuli, scars, and breakage clearly visible. Therefore, it is reasonable to expect that photographs and subsequent photogrammetry analyses will provide a reliable, non-invasive approach to studying the variation in horn morphology amongst living bighorn sheep rams.

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KEY WORDS: monitoring, management, non-invasive, photography, ram horns, sexually selected traits

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INTRODUCTION

Sexually selected traits such as weaponry, bright colours, and body size are often correlated with an individual male's fitness (Darwin 1871, Fisher 1915). However, very often studies of these traits are done on captive or diseased individuals if they are not regularly caught and measured. While exploring different ways to measure secondary sexually selected traits in bighorn sheep (*Ovis canadensis*), such as horns, we identified some issues with these measurements in that they are routinely completed for deceased bighorn rams, either individuals that have been legally hunted under minimum harvest size regimes, were found dead or were confiscated. Additionally, for monitored populations, measurements are done at the time of capture, which tends to occur during the first few years of an individual's life. Thus, the data sets compiled by this approach are inherently biased towards larger males, as those are the ones that are targeted by trophy hunting (Festa-Bianchet *et al*. 2015, Festa-Bianchet 2017, Pelletier *et al*. 2012). Therefore, the measurements of deceased individuals are not necessarily representative of all males in a population which complicates the assessment of the impact of hunting, environmental pressures, demographic pressure and disease on horn growth (Festa-Bianchet and Mysterud 2018).

Male Rocky Mountain bighorn sheep are an ideal study organism as their exclusive trophy harvest is closely monitored, making manual growth measurements available for study through the government agencies and long-term projects. Additionally, annuli allow for age determination (Geist 1966) and digital measurement of annual growth. Furthermore, large horn size is correlated with a higher rank in the mating hierarchy (Geist 1971). As there is a high mating skew for bighorn sheep rams, the tending or high-ranking males enjoy higher reproductive success than subordinate males (Geist 1971, Hogg and Forbes 1997). Lastly, horn size is a heritable trait with a reported h^2-value of 0.397 (Pigeon *et al*. 2016). Therefore, the systemic removal of dominant rams, with rapid horn growth rates, has the potential to drastically alter the age structure of the population (Schindler *et al*. 2017) and the reproductive success of the survivors which could, over time, cause a decline in horn size (Coltman *et al*. 2003, Pigeon *et al*. 2016, Schindler *et al*. 2020).

Previous work on Ibex (*Capra ibex*) has shown that total and annual horn growth can be reliably measured using photographic techniques (Bergeron 2007, Willisch *et al*. 2013). However, ibex have relatively straight horns in comparison to those of bighorn sheep. To our knowledge, photographic measuring techniques have not been tested and calibrated for animals with curled horns. Thus, given, the bias in existing datasets, we decided to investigate whether the size and annual growth of bighorn ram weaponry (horns) could be accurately measured using non-invasive photographic techniques, specifically using photogrammetry and 2D measurements on photographs from live animals. Our second goal was to use photogrammetry to build 3D models that could provide scaled depictions of a male's horn size and shape. If these models are accurate, then more detailed measurements could be taken and dimensions calculated (i.e., the volume of yearly horn growth, entire horn volume). In this paper, we discuss the 2D measurement techniques and the development of 3D models, comparing them to manual measurements. Our study shows that these techniques reflect manual measurements of live or dead animals very closely and propose that these be considered in lieu of captures or working on dead animals exclusively.

METHODS

Study Organism and the Long-term Database

The bighorn sheep population at Sheep River Provincial Park (SRPP), Alberta, Canada, is part of a long-term study and therefore a long-term photographic data set (compiled by Dr. Kathreen Ruckstuhl and her collaborators since 2006) is available. As part of the long-term monitoring project, the bighorn sheep are captured primarily as lambs. During capture, DNA is collected, and the individual is fitted with ear tags that correspond to a unique identification number (Ruckstuhl 1998). Therefore, over 90% of the sheep are individually identifiable through ear tags, which enables tracking them throughout their lives.

STUDY AREA

This study was conducted in Sheep River Provincial Park located in Kananaskis, Alberta, Canada (50º38'55" N 114º37'38" W) from the University of Calgary's R.B. Miller Field Station. The region is located on the eastern slopes of the Rocky Mountains and is dominated by grasslands, pine, and aspen forests as well as a river canyon and open meadows.

Photographic Techniques

The first photographic technique we explored was 2D digital measurement of annual growth. Photos of rams, with known scales (Fig. 1.) were loaded into ImageJ (Abramoff *et al*. 2004, Rasband 2018) allowing for the measurement of annual growth. Two methods of including known scales in the photographs were calibrated. 1) Photos were taken with parallel laser points projected onto the ram's horn spaced 4 cm apart (laser setup method adapted from Bergeron, 2007). 2) The ear tags are a standard shape and size and therefore their height (3.7cm) can also be used as a known scale. We recommend using the height of the ear tag as opposed to the width as the width can be distorted in images due to the position of the ram's ears within a 2D plane. However, the height of the ear tags does not change regardless of ear position. Digital measurements were compared to corresponding manual measurements taken post-mortem and/or during capture using linear regressions that were forced through the origin. Our sample size was 65 annuli from nine rams aged two to ten years old.

The second photographic technique we explored was photogrammetry. We mounted the horn of a deceased eight-and-half-year-old ram onto a rotating pedestal. Using a tripod, 200 photos were taken while rotating the horn roughly 1 cm between shots; photos were taken with the camera positioned beneath, level with, and above the horn. Using the software AgiSoft Metashape Professional (2020), these photos were aligned using 200,000 points to create a point cloud (Fig.2. Left) A mesh was then applied to connect the points and eliminate outlying points thereby creating a solid computer model (Fig. 2. Middle). Finally, the model was textured which involves adding fine details and colour to the exterior layer (Fig. 2. Right). The final model was then 3D printed. Both the virtual and physical model were visually compared to the real horn.

RESULTS

2D Measurement

The comparison between digital measurements done in ImageJ (Rasband 2018) and the manual measurements was a close match (Fig. 3 and 4). Overall, the digital measurements were accurate to within 5mm of the manual measurements.

Photogrammetry Generated 3D Model

Using photogrammetry, we produced a 3D print of a horn from an eight-and-a-half-year-old deceased ram. Through visual comparison of both the digital and physical 3D model, we determined it to be an accurate representation of the actual horn (Fig. 5). The annuli and markings on the horn were clearly visible and the spread mirrored that of the real horn (Fig. 5). Thus, 3D models could be used as a non-invasive tool to determine annual growth patterns for living individuals and growth increments could be measured either by the length and circumference of the annuli, or the volume of growth be further calculated.

DISCUSSION

Using 2D photo analysis and photogrammetry, we have demonstrated that the size, shape, and breakage of bighorn ram horns can be evaluated while the individual is alive without necessitating capture. This allows researchers to assess the weaponry size of living individuals non-invasively. Some limitations must be taken into consideration though. For 2D digital measurement of annual growth to be successful, numerous profile and head-on photos are needed where the individual of interest is the main subject in the photo. If the bighorn sheep are marked, ear tags provide a reliable, known scale as ear tag dimensions are standardized. Alternatively, we have shown that for unmarked rams using parallel laser pointers and a camera, very precise measurements can be taken from live animals in the field. Furthermore, if using ear tags and/or laser pointers as known scales is not feasible (i.e., studying unmarked animals from a distance

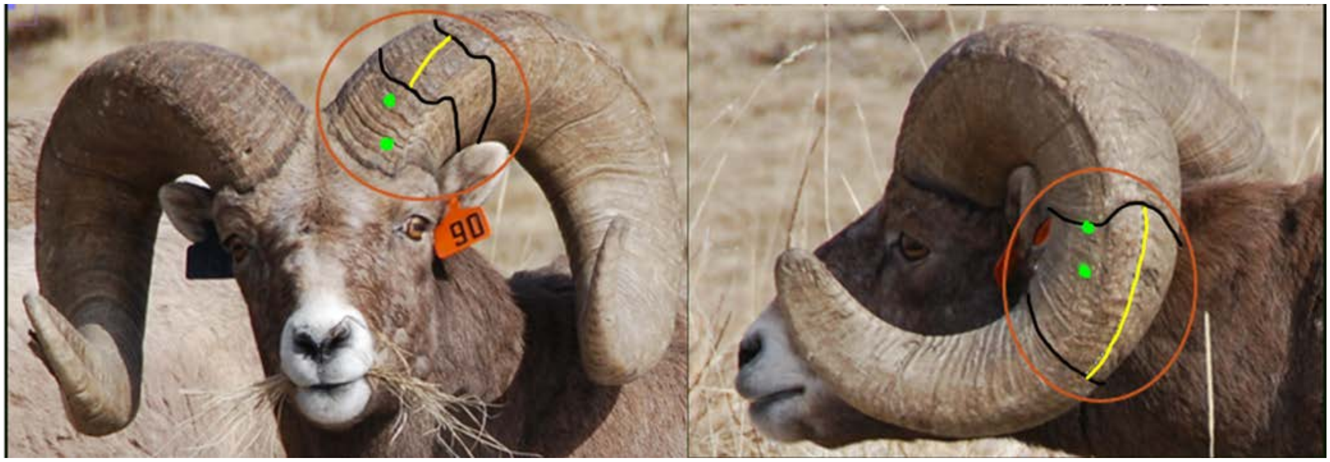

Figure 1. A photographic example of a digital 2D measurement of the annual horn growths of a bighorn ram (ram ID=706). Annuli (grooves where horn growth was arrested during winter) are indicated in black. Laser points are the green-filled dots, representing 4 cm between them (centre to centre). The yellow line shows the measurement for one year's (annual) growth. Note the ear tag height (3.7 cm) can be used as a known scale. Photo credit: K. E. Ruckstuhl.

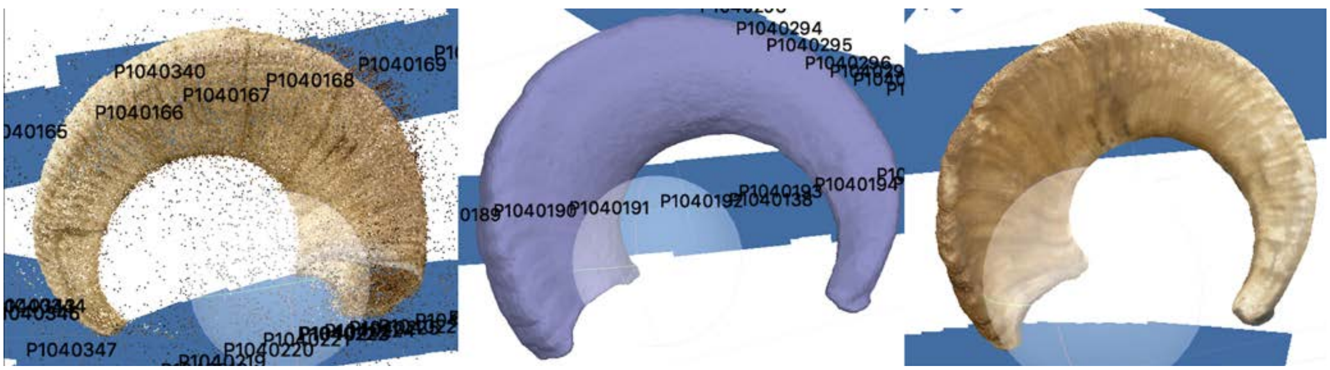

Figure 2. The stages of creating a digital 3D model of an eight-and-a-half-year-old ram's horn in Agisoft Metashape Professional (2020). On the left is the point cloud model. In the middle is the mesh model. On the right is the final, textured computer model. Blue squares and associated writing correspond to the position of individual photographs. Model/ photos by T.C. Henry.

greater than ~50m) scaling objects in the vicinity (such as trees, rocks, road markers or rams with known horn measurements) may provide an accurate alternative (Willisch *et al*. 2013) so long as the scaling object and the ram of interest are photographed in the same plane.

Although, we were successful in creating a digital 3D model and a print from a deceased individual, photos were taken in the lab, with known angles. Thus, the challenge will now be to evaluate how many pictures need to be taken of a living ram to be able to create precise 3D models. Our recommendation is to take pictures of individuals while they are standing or bedded, and enough photos can be taken from different angles, while they are relatively sedentary.

Overall, we believe that non-invasive photographic techniques provide a promising method of assessing the horn size of live individuals without the need for repeated captures, thus facilitating future studies on the evolution, growth and use of sexually selected weaponry. This would allow researchers to obtain data that is more representative of the entire population and

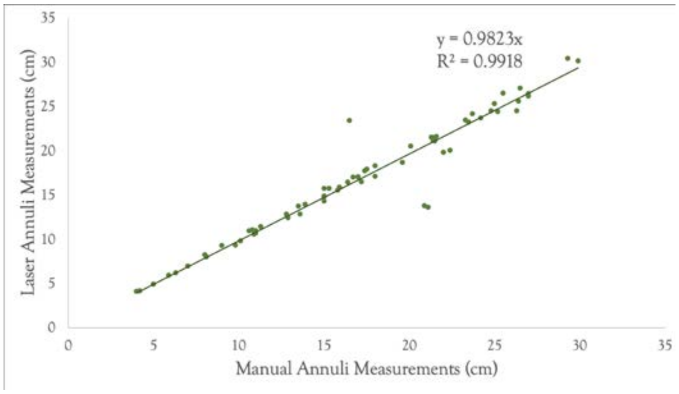

Figure 3. Comparison of manual and digital measurements (cm) of annual growth. The digital measurements were taken using photographs of rams with parallel lasers spaced 4 cm apart projected onto the rams' horns as a known scale. The sample size is 65 annuli from nine rams aged two to ten years of age. Note, the linear regression was forced through the origin.

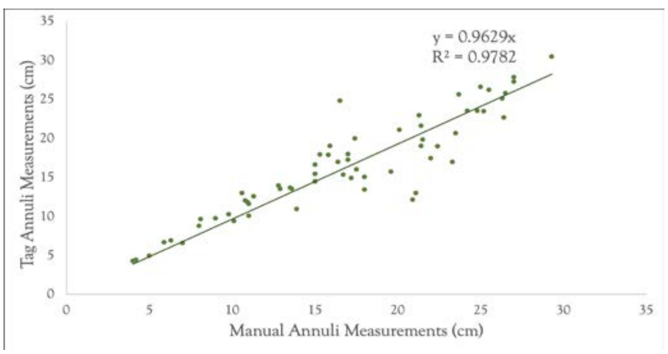

Figure 4. Comparison of manual and digital measurements (cm) of annual growth. The digital measurements were taken using photographs of rams with the height of ear tags (3.7 cm) as a known scale. The sample size is 65 annuli from nine rams aged two to ten years of age. Note, the linear regression was forced through the origin.

Figure 5. Visual comparison of a photograph of a horn from a deceased eight and half year-old ram to the 3D printed model of the horn. Note the visibility of the annuli, breakage, and shape. Model and photo by T.C. Henry.

not biased towards deceased larger males who are almost exclusively hunted for sport. Once this method is standardized, it can be applied to any size and shape of sexually selected traits.

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Cost Distance Models to Predict Contact Between Bighorn Sheep and Domestic Sheep

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ABSTRACT: Infectious disease transmission from domestic sheep threatens the persistence of bighorn sheep (*Ovis canadensis)* populations throughout western North America. Quantifying spatial separation between the two species is an essential component in assessing the risk of disease transmission. We present a spatial analysis to evaluate infectious disease risks for endangered Sierra Nevada bighorn sheep (*O. c. sierrae)*. We combined a resource selection probability function with a cost distance analysis to quantify the risk of grazing domestic sheep in proximity to Sierra bighorn sheep core home range from a habitat perspective. Our approach accounted for the spatial separation between the species as well as the configuration of resources that influenced Sierra bighorn sheep movement. We assessed the potential for contact by predicting where Sierra bighorn sheep were likely to travel. Our method established a risk threshold which could be used to optimize grazing regimes of public land allotments, private leases and hobby farms. We compared our approach to a standard buffer approach and determined that our cost distance model better quantified how risk varied among parcels that are located equidistant from Sierra bighorn sheep core home range. Sierra bighorn sheep clearly selected and traveled within habitat that provides escape terrain. Our model, which included a log normal transformation, characterized the high relative cost (i.e., reduced likelihood) to traveling beyond selected habitat and predicted that such movement is less likely. As a result, our habitat-based risk threshold was 48% smaller in area than the standard buffer area that included landscape which bighorn did not use. Our framework offers a quantitative method for land managers to evaluate domestic sheep grazing and the potential for co-habitation to minimize the risk of disease transmission.

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KEY WORDS: contact, cost-distance analysis, disease transmission, domestic sheep, Sierra Nevada bighorn sheep.

Assessing the Performance of the Risk of Contact Tool's Core Herd Home Range Estimator

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ABSTRACT: The US Forest Service/Bureau of Land Management's Risk of Contact Tool (RoCT) informs bighorn sheep managers by providing them with quantitative estimates of risk of contact between foraying bighorn sheep and domestic sheep and goats. The Tool implements a model originally developed for a 2010 bighorn sheep viability analysis by the Payette National Forest. That analysis was based on 13 years of mostly VHF telemetry data, collected at approximately two-week intervals from animals in 12 Hells Canyon area herds. While the Tool gives users wide latitude in their choice of inputs, several of its defaults reflect aspects of that original dataset. Advances in both animal tracking technology and modeling methodologies since the Payette analysis spurred reassessment of one of those defaults, the Gaussian reference function kernel density estimator (KDE) that the Tool uses to estimate a Core Herd Home Range (CHHR). The KDE assumes that location data are independent and identically distributed – an assumption that is violated by the high-fix-rate, highly autocorrelated location data provided by GPS collars. To remedy that issue, Silverman et al. (2015) propose using the autocorrelated KDE (AKDE), which they designed to account for the autocorrelation inherent in modern tracking data. Accordingly, we compared the performance of the KDE and the AKDE, along with two other commonly used home range estimators, the minimum convex polygon (MCP), and local convex hull (LoCoH). To compare the estimators, we used a GPS dataset consisting of locations from nearly 600 animals in 60 Nevada herds. Estimator performance was assessed at both the individual and the herd level using several forms of subsampling and cross-validation. For each home range estimate, we measured area along with coverage with respect to both in-sample and out-of-sample telemetry points. A good home range estimate is one that comes close to achieving the desired coverage (e.g. encompassing 95% of out-of-sample points) while remaining relatively small. Based on those criteria, and despite the high spatial autocorrelation of the telemetry data, the KDE estimator currently used by the Tool performs as well as, and in most aspects better than, the three alternatives we assessed.

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KEY WORDS: bighorn sheep, core herd home range, risk of contact tool, viability analysis.