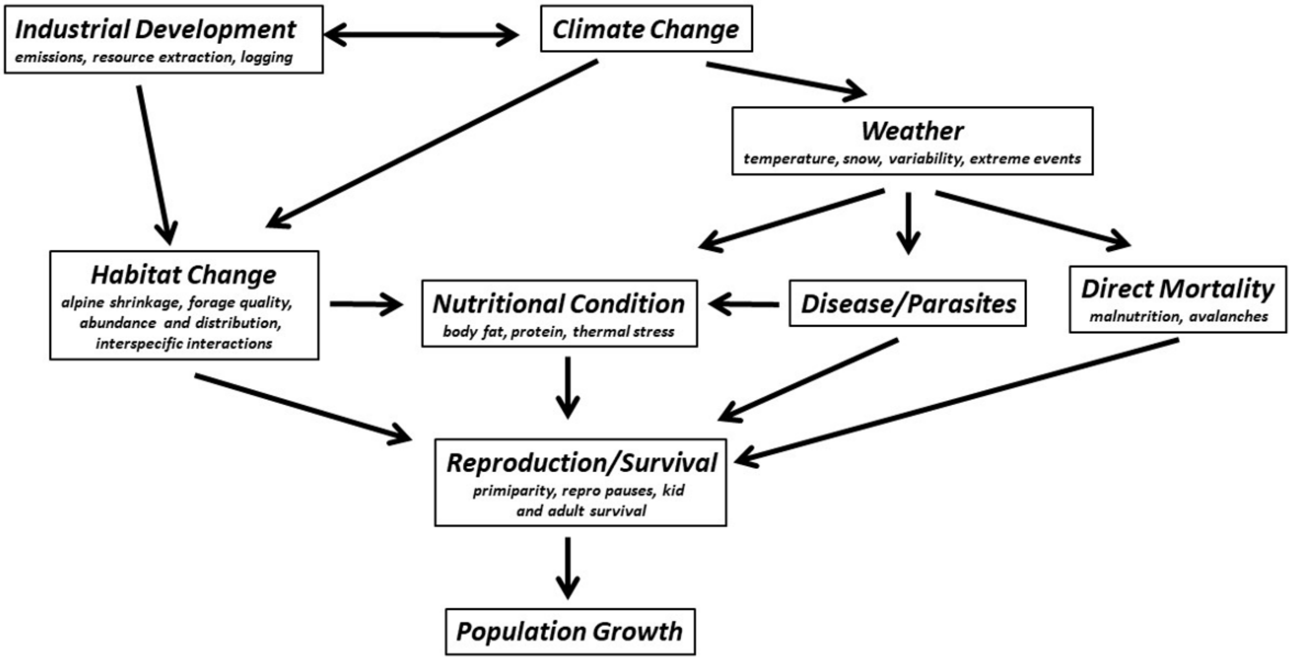
NORTHERN WILD SHEEP AND GOAT COUNCIL POSITION STATEMENT

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).

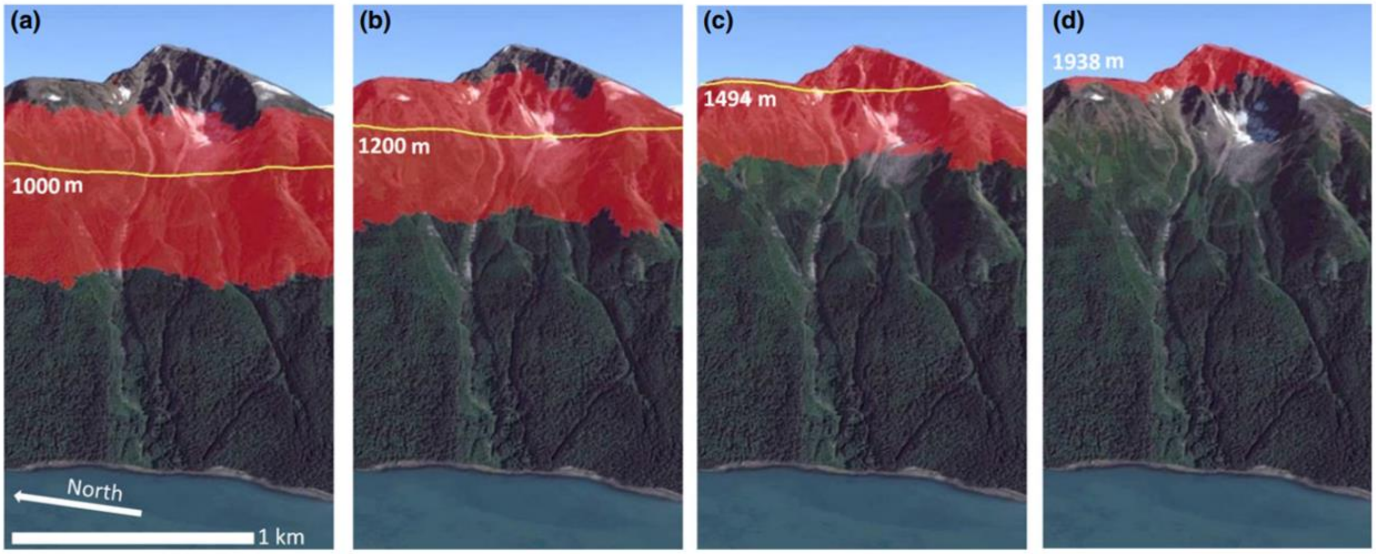
b. Climate-mediated landscape/habitat changes

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)



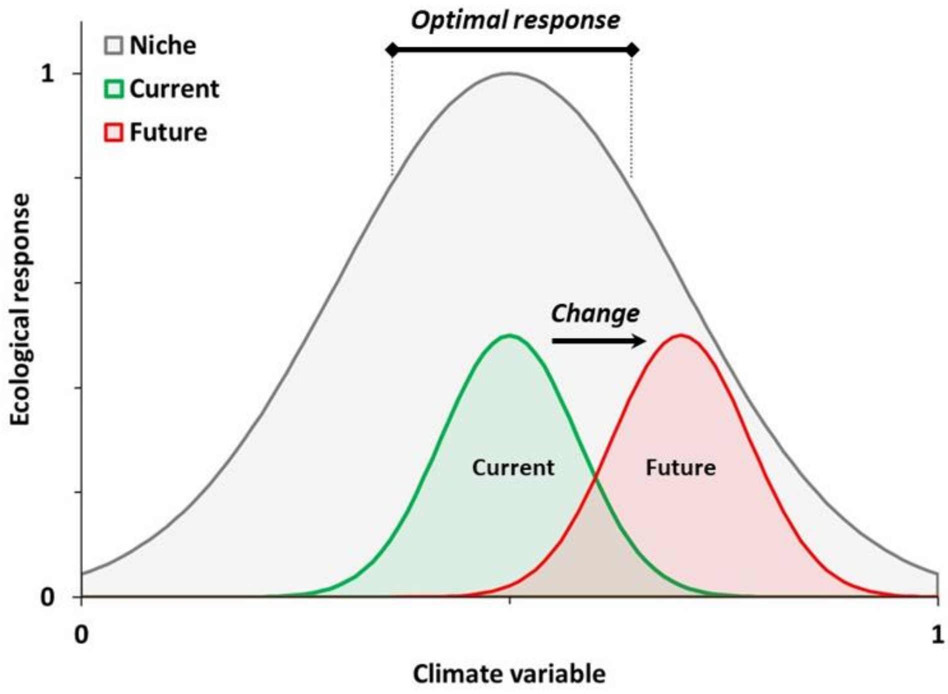
In drier, more interior areas, warming summer temperatures associated with climate change may increase the frequency, intensity and geographic extent of wildfires. Such events can destroy important forested winter range habitats and have detrimental effects on local and regional mountain goat populations. 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

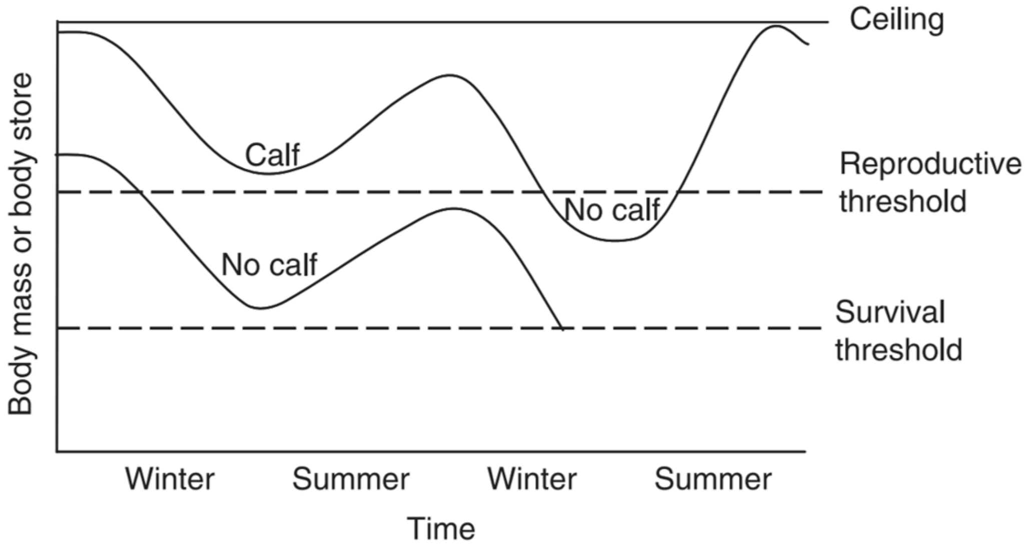
Understanding how climate change affects mountain goat population ecology can be difficult to examine because it requires long-term studies (i.e. climate is generally defined as weather patterns over a 30+ year period). Thus, much of our knowledge about how climate may affect mountain goats is derived 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).