Assessing Alpine Ecosystem Vulnerability to Environmental Change Using Dall Sheep as an Iconic Indicator Species

Final Report

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A nursery band of Dall sheep in Wrangell St-Elias National Park, Alaska (photo: L. Prugh).

1) Project Objectives

Lack of knowledge about climate change impacts in alpine ecosystems represents a critical gap in our understanding of resilience and vulnerability to environmental change in the Arctic and boreal region of western North America. Declines in Dall sheep populations throughout their range have led to emergency harvest closures and made sheep harvest by far the most contentious wildlife management issue in Alaska. Dall sheep likely function as bellwethers of alpine ecosystem health, and signs are pointing towards increasing ailment. **The overarching goal of our study was to address the question: How are vegetation and snow conditions changing in alpine ecosystems throughout the ABoVE domain, and how do these changes impact iconic northern wildlife and critical ecosystem services?**

This project had 4 specific objectives:

(1) Produce time series of snow extent, NDVI, and shrub encroachment throughout alpine areas of the ABoVE domain
(2) Evaluate how these factors affect Dall sheep movements, habitat selection, and population viability
(3) Validate and apply a spatially-explicit snowpack evolution model to produce maps of snow properties at a spatial resolution relevant to wildlife management
(4) Relate our improved understanding of alpine ecosystem dynamics to the societal implications of altered sheep harvest.

2) Accomplishments

Summary

We conducted the following major activities during the 4-year grant period:

1) *Data synthesis*. We established data sharing agreements with the Alaska Department of Fish and Game, National Park Service, US Fish and Wildlife Service, Bureau of Land Management, Gwich'in Renewable Resources Board, Parks Canada, Environment Yukon, and Government of Northwest Territories. Through these agreements, we synthesized Dall sheep aerial survey data (*n* = 4,356 surveys, 1934-2015), 12 radio telemetry datasets (*n* = 582,193 locations from 498 collared sheep, 1983-2018), and sheep harvest records from 1983-2015.
2) *Fieldwork*. We developed a new method for collecting hourly ground observations of snow depth in remote, roadless areas of the ABoVE domain using game cameras and Google TensorFlow technology to automate image processing. We conducted 7 field expeditions in the Wrangell Mountains to install stations and conduct snow surveys (*n* = 7,600 snow depth records from Magnaprobe surveys and 320,000 records from remote camera stations; stratigraphy, depth, and hardness from 103 snow pits).
3) *Remote sensing*. We developed new regional products of alpine snow cover and NDVI using MODIS sensor data throughout the ABoVE domain. We used Landsat

imagery, orthorectified historical photographs, and current NGA Worldview imagery to identify potential areas of shrub expansion in alpine areas.

4) *Modeling*. We used SnowModel to evolve the snowpack over 6 focal study areas in Alaska, using our extensive ground observations in the Wrangells for cal/val. We integrated the synthesized Dall sheep data with remote sensing and gridded meteorological products, and we used a variety of models to examine how these environmental factors affect Dall sheep populations and harvest levels.
5) *Stakeholder engagement and outreach*. We engaged with our agency collaborators during bi-monthly project conference calls, and we have given several talks about the project to the public, agencies, and at wildlife meetings in the ABoVE domain. We also communicate with our stakeholders and the public through our project website: https://dallsheep.weebly.com/. Our findings were also shared with the public through news articles, blog posts, and public talks.
6) *Dissemination to the scientific community*. Our project produced 11 scientific manuscripts that are either in review (3) or published (8). We have archived 6 datasets at the ORNL DAAC (with two more in preparation), which have been downloaded 938 times. We also disseminated findings through 18 presentations at scientific conferences hosted by 8 different professional societies.

These activities have revealed several important new insights:

1) The timing of spring snow melt is critically important for Dall sheep productivity, especially at high latitudes (Verbyla et al. 2017, van de Kerk et al. 2018), but snow depth in the preceding fall may have an even stronger effect (Cosgrove et al. in review). Thus, a greater understanding of shoulder season snow dynamics is needed to predict climate change impacts on wildlife.
2) While snow cover and snow depth have been the focus of most snow-wildlife studies, our findings indicate that snow density is an important snow property affecting Dall sheep movements (Mahoney et al. 2018, Sivy et al. 2018).
3) The most informative snow product for predicting sheep movements is scale-dependent: modeled depth and density is best at fine-scales, whereas MODIS fractional snow cover is best at coarse-scales (Mahoney et al. 2018, Boelman et al. 2019).
4) Remotely-sensed summer productivity (max NDVI) and winter freeze-thaw events (from passive microwave satellite retrievals) are better predictors of sheep survival than meteorological data (van de Kerk et al. in press), with frequent freeze-thaw events reducing sheep survival. These findings indicate that warming may adversely affect sheep by forming ice layers over ground forage.
5) The regional relationship between NDVI and precipitation is fundamentally different in relatively warm vs. cold regions of the ABoVE domain, which may provide a vital key to understanding regional differences in sheep vulnerability to climate change (Verbyla and Kurkowski 2019).
6) Fall weather has a strong effect on sheep harvest success, indicating climate change may directly affect hunter success in addition to its effects on sheep populations (Leorna et al. in review).

Accomplishments led by each PI and co-PI are described below.

PI Laura Prugh (University of Washington)

PI Prugh supervised postdoc Madelon van de Kerk and research scientist Kelly Sivy in Years 1 and 2. Prugh was a member of the Wildlife and Ecosystem Services and Stakeholder Engagement working groups, and she participated in all science team meetings. Her team was responsible for Objective 2, examining the impact of environmental variables on Dall sheep movements and demography. Prugh, van de Kerk, and Sivy participated in field expeditions, led outreach communications (including designing and maintaining the project website), compiled Dall sheep datasets, and published manuscripts.

Fieldwork. We conducted 6 field campaigns in Years 1-3 in Wrangell St-Elias National Park and Preserve. Prugh led the campaigns in Year 1, and PhD student Chris Cosgrove (Oregon State University) led the field campaigns in Years 2 and 3, with Prugh as a team member. The ABoVE Logistics Office in Fairbanks provided resources and logistical support that were invaluable to the success of these efforts, especially the lending of snowmachines, winter camping gear, safety trainings, safety equipment, and assistance from Sarah Sackett. We established 22 snow depth stations on Jaeger Mesa in September 2016, conducted snow surveys in March 2017, moved stations to a new study area in August and September 2017, conducted snow surveys in March 2018, and removed stations in June 2018. Snow surveys consisted of snow depth transects using a Magnaprobe (n = 2,700 measurements), snow pits at each camera station to record snow stratigraphy (n = 103 pits), and measuring Dall sheep and coyote snow track sink depths and associated snow properties (n = 69 track sites). Camera stations recorded hourly snow depth and temperature measurements throughout the snow-covered season (n = >320,000 photos).

Snow track measurements were used to determine the snow density threshold for supporting the body mass of Dall sheep and coyotes, which are major predators of Dall

Figure 1. Snow surveys in Wrangell St. Elias National Park, March 2017 and 2018. Left: Sivy measures snow depth and density at a set of Dall sheep tracks. Center: Prugh checks a snow depth monitoring station. Right: Prugh measures snow depth with a Magnaprobe.

sheep. The density threshold to support the body mass of Dall sheep was estimated to be 329 kg/m^3 (Sivy et al. 2018), and the estimated threshold to support a coyote was 270 kg/m^3 (Figure 2). Thus, we identified a "danger zone" for Dall sheep between 270-329 kg/m^3, because snow densities within this range allow coyotes to run on top of the snow but Dall sheep will sink into it. These estimates will allow us to model how changing snow conditions will affect predator-prey dynamics for the first time, which will be a ground-breaking achievement of broad applicability to wildlife management in the ABoVE domain and beyond.

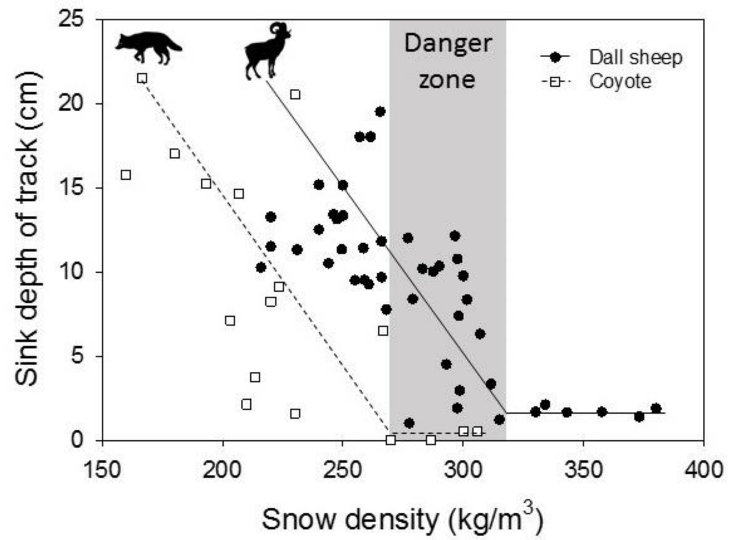

Figure 2. Breakpoint regression was used to find thresholds of snow density for supporting the weight of coyotes and Dall sheep (i.e., densities where snow track sink depths are ~0-2 cm). These thresholds reveal a "danger zone" between 270-329 kg/m^3 where coyotes can run on top of the snow but Dall sheep sink in, making them more vulnerable to predation.

Effects of snow properties on sheep movements. Prugh's team led a collaborative paper in the Wildlife and Ecosystem Services working group, in which the effects of modeled and remotely-sensed snow properties on Dall sheep movements were examined at multiple scales (Mahoney et al. 2018). This was the first study that included snow properties in analyses of wildlife GPS location data. We found that adding any snow product significantly improved model fit. At fine scales, Dall sheep movements were best described by snow depth and density modeled at 25-m resolution using SnowModel. However, MODIS performed surprisingly well at coarse (500m-2km) scales, outperforming SnowModel as a predictor of broad-scale sheep movements. This study was also included as a case study in the Wildlife and Ecosystem Services working group review paper calling for greater integration of wildlife science and snow science (Boelman et al. 2019).

Effects of snow properties on sheep demography. We used MODIS-derived snow cover products developed by co-PIs Verbyla and Nolin and our sheep survey database to determine how snow conditions affect sheep recruitment (van de Kerk et al. 2018). We found late spring snow cover negatively affected recruitment, and this effect strengthened with latitude. These results show that climate impacts can vary strongly across a species range, which needs to be considered when predicting climate-induced species range shifts.

Next, we used GPS and VHF telemetry data from 498 radio-collared Dall sheep in 9 areas of Alaska and Canada from 1997-2012 to examine factors affecting survival (van de Kerk in press). We developed environmental covariates based on gridded climate data and remote sensing products, and we examined the effect of these covariates on sheep using survival models. We found that lamb survival was most strongly affected by maximum summer NDVI, whereas adult survival was most strongly affected by the freeze-thaw frequency (FTF) in the previous winter based on satellite measures of radiometric brightness (Figure 3). In addition, these remotely-sensed environmental factors interacted with meteorological factors to affect survival, such that effects of winter temperature depended on summer NDVI and winter FTF. Warm winters increased lamb survival only when preceded by summers with high NDVI, and warm winters increased adult survival only when winter FTF was low. Thus, potential benefits of climate warming may be counteracted if wintertime freeze-thaw events markedly increase. Correlations among environmental variables across sites were low, and regional climate cycles such as the Pacific Decadal Oscillation had weak effects, indicating substantial local variability in climatic conditions experienced by Dall sheep across their range. These findings can help managers anticipate how Dall sheep populations will respond to changes in local environmental conditions. Our results also highlight the utility of multiple remotely-sensed environmental conditions for ungulate management, especially passive microwave products that provide valuable information on winter icing events.

Outreach and stakeholder engagement activities. Prugh conducted several outreach and stakeholder engagement activities. She gave an Earth to Sky webinar about the project on June 14, 2016 that was attended by 20 people. She gave a talk and participated in the 2-day NASA Earth To Sky *Interpreting Climate Change* workshop in Spokane WA Nov 13-14, 2017. She gave a public lecture about the project as part of the Wrangell Institute for

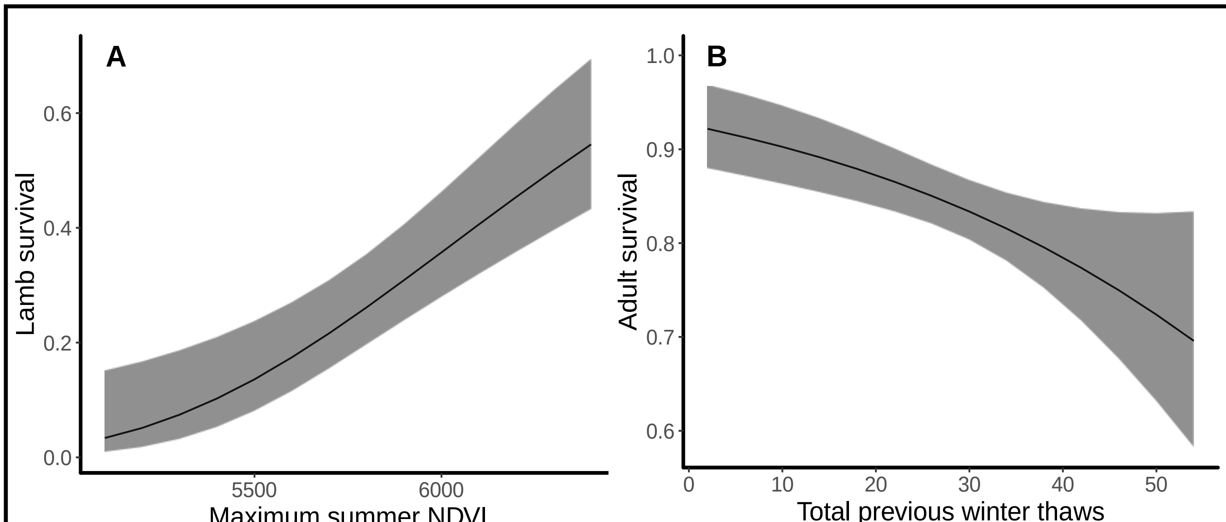

Figure 3. (A) The effect of maximum summer NDVI on Dall sheep lamb survival and (B) the effect of the number of thaws in the previous winter on adult survival (van de Kerk et al. in press).

Science and Environment Science Lecture Series in Wrangell-St Elias National Park on March 13, 2018, and she gave a talk about the project at the Alaska Department of Fish and Game in Fairbanks on March 22, 2018. She wrote a blog about the March field trip for the NASA Earth Observatory "notes from the field" blog in May 2018, and she was a panelist at a press conference on climate change and wildlife at AGU in New Orleans on December 11, 2017. Prugh led teleconferences with the project team to coordinate activities and maintain communication among lab groups and agency collaborators. Meetings occurred every other month and typically included 14-20 participants. These meetings were a great way to engage with our agency collaborators.

Co-PI David Verbyla (University of Alaska Fairbanks)

Co-PI Verbyla supervised MS student Mark Melham, and his team was responsible for Objective 1 (developing remotely-sensed time series of NDVI, snow cover, and alpine shrub expansion). Verbyla was a member of the Vegetation Dynamics and Distribution Working Group and participated in the ASC webinars. He was an active user of the ABoVE Science Cloud.

Alpine snow cover. Verbyla's first project developed a novel application of MODSCAG, in which the spring snowline elevation was estimated each year from 2000-2016 within 28 mountain areas (Verbyla et al. 2017). The elevation of spring snowline is important for Dall sheep and other alpine species. A late spring and low snowline elevation could delay plant phenology and reduce forage availability and quality. In addition, snow cover may hamper movements and increase the risk of predation. We used Landsat OLI surface reflectance to compute a Normalized Difference Snow Index (NDSI) to validate our MODSCAG based estimates of elevation of spring snowline.

Alpine NDVI. Next, Verbyla led a study to examine how maximum NDVI varied among mountain ranges with respect to elevation and climate from 2002-2017 (Verbyla and Kurkowski 2019). We used the annual maximum NDVI data from the 250-m MODIS NDVI product as a proxy of maximum growing season photosynthetic activity. The long-term average (16-year, 2002-2017) and interannual pattern of maximum NDVI was investigated with respect to elevation, July temperature, and July precipitation classes within 4 climatic mountain regions: (1) Cold Arctic (Northern Brooks Range), (2) Arctic (Southern Brooks Range), (3) Interior, and (4) High Precipitation (Southcentral Coastal Alaska). The July temperature lapse rate was consistently linear while the long-term maximum NDVI lapse rate was non-linear. The High Precipitation region had the highest NDVI at lower elevations, while the Interior Mountains region had the highest NDVI at higher elevations. The long term maximum NDVI was negatively correlated with July precipitation for areas with July temperature 12°C or colder, whereas NDVI was positively correlated with July precipitation in areas with July temperature above 12°C (Figure 4).

Cold temperature was likely limiting vegetation productivity as indexed by maximum NDVI across a wide range of high latitude mountains in Alaska and the Yukon Territory. At relatively warm July temperatures, moisture may be limited in the Interior

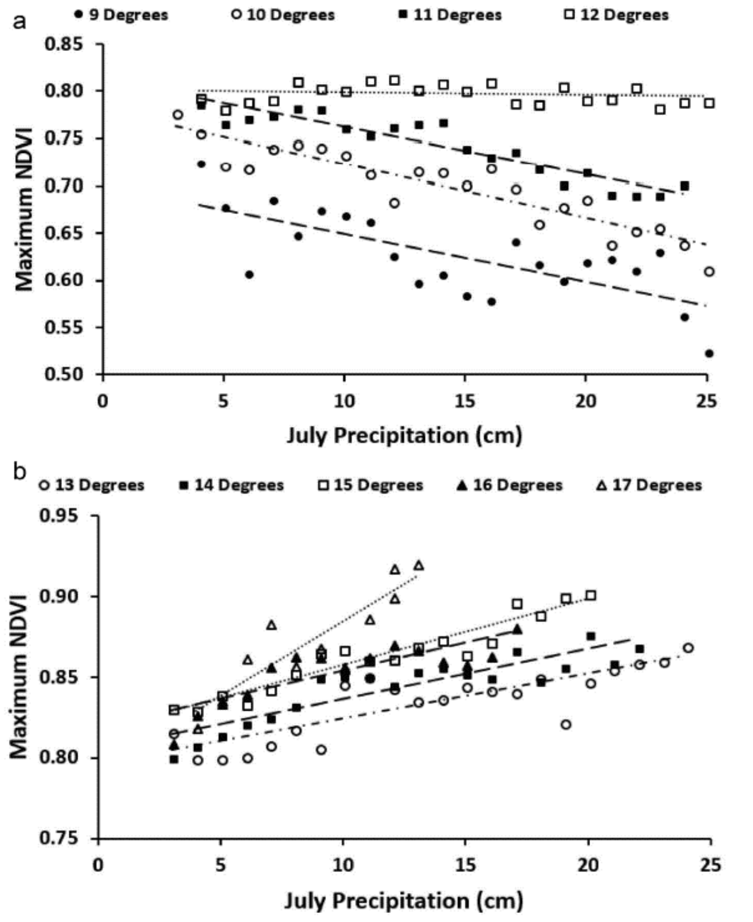

Figure 4. (a) Long-term maximum NDVI decreases with July precipitation in mountain regions where mean July temperature is 12°C or colder, whereas (b) max NDVI increases with July precip in regions where mean July temp is above 12°C.

Mountains region, as the High Precipitation region consistently had the highest mean NDVI at July temperatures above 12°C. If the climate continues to warm with no significant increase in precipitation, moisture stress may become an important factor limiting vegetation productivity in the Interior Mountains region of the ABR.

Alpine shrub expansion. The final project led by Verbyla's team was to examine change in shrub dominance within the Dall sheep range over the last 30 years. Encroachment of shrubs into alpine systems may negatively impact alpine specialists such as Dall sheep. Increased snow depths due to shrub expansion can restrict winter movements, reduce forage availability, and provide increased habitat for coyotes and wolves, which are important predators of Dall sheep. Research on shrub expansion has been primarily focused on localized regions, such as the Arctic coastal plain, in controlled study areas (e.g. open top chambers), and at lower elevations (e.g. Arctic riparian corridors). We examined shrub expansion across Alaska's alpine systems to quantify regional rates of shrub expansion in relation to climatic factors, with a focus on lower temperature limits of shrubs.

Satellite imagery was converted to maps of percent shrub cover in alpine areas and used to infer climatic drivers of multidecadal shrub change along a climatic mountain gradient. We sourced Landsat-8 Operational Land Imagery (OLI) scenes dating from the modern era (defined as 2013 – 2018; hereafter referred to as modern) and Landsat 4-5 Thematic Mapper (TM) scenes dating from the historic era (defined as 1984 – 1989; hereafter referred to as historic) occurring within July and containing 70% or greater cloud-free pixels. Using data from the 2011 National Landcover Classification Database (NLCD), we removed known forests from consideration for analysis. NDVI was used to calculate percent shrub dominance based on red and near-infrared bands. To process these bands for the NDVI calculation, we first used ENVI 5.5.1 (API version 3.3) to calibrate reflectance of the red and near-infrared bands (spatial data layers that contain single numerical values within each pixel representative of a specific type of light /electromagnetic radiation) for modern OLI (bands 4 and 5 respectively) and historic TM (bands 3 and 4 respectively). Using these calibrated bands, we isolate completely cloud-free areas that could be used for analysis.

Percent shrub increase during the 30-year period ranged from 5.8-8.1%, with highest change the Cold Arctic alpine regions and substantial variability within regions (Table 1). Areas with temperature exceeding growth temperature minimums for shrubs showed significantly higher rates of shrub change compared with areas at or just above growth temperature minimums. These findings are currently being finalized for publication.

Table 1. Change in percent shrub dominance between historic (1980s) and modern (2010s) eras in Dall sheep mountain habitat.

Mountain Region	% Shrub (SD) Historic	% Shrub (SD) Modern	% Change (SD)
Cold Arctic	30.8 (13)	38.8 (17.2)	8.1 (7)
High Precipitation	42.7 (22.4)	48.9 (24.1)	6.3 (9.5)
Interior	31.3 (8.6)	37.4 (12.3)	6.1 (12.9)
Arctic	23.9 (9.5)	29.6 (13.3)	5.8 (5.7)

Co-PI Anne Nolin (Oregon State University)

Co-PI Nolin supervised PhD student Chris Cosgrove, and her team was responsible for Objective 3 (developing fine-scale maps of snow properties using a physically-based snow evolution model, SnowModel). Nolin served as a liason between ABoVE and the SnowEx campaign.

Fieldwork. Nolin participated in the September 2016 and March 2017 field expeditions, and PhD student Cosgrove participated in or led all field expeditions. These field activities were described in more detail in PI Prugh's section above.

Snow modeling in the Wrangells. Wrangell St-Elias National Park and Preserve is home to 20% of the world's population of Dall sheep, and 25% of the Alaskan sheep harvest occurs in this area. Using our field data in the Wrangells to calibrate SnowModel, we examined the seasonal influence of different snow properties on Dall sheep productivity (Cosgrove et al. in review). We produced a calibrated and validated 30 m resolution, daily simulation of snow properties within our ~40 km by ~50 km study domain from September 1980 to August 2017. We calculated snow depth, snow density, total snowfall, and a "forageable area" index for fall, winter, and spring seasons during this 37-year

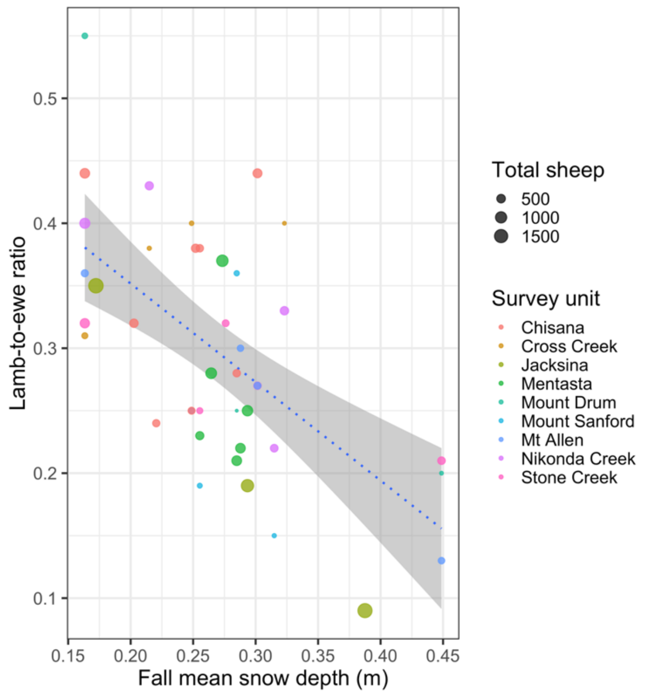

Figure 5. An increase in Fall mean snow depth decreases Dall sheep summer productivity, here defined as lamb-to-ewe ratio from summer sheep surveys (*n* = 41). The shaded grey area is the 95 % confidence interval.

period. Forageable area was calculated as the percentage of Dall sheep habitat with snow depth beneath half-chest height and snow density beneath 330 kg/m^3 (these values were based on thresholds identified by Mahoney et al. 2018 and Sivy et al. 2018). We used linear regression to examine relationships between these snow metrics and sheep population productivity in subsequent summers, measured as the lamb-to-ewe ratio obtained from summer aerial surveys.

Fall mean snow depth was the strongest predictor of Dall sheep productivity, with an increase in mean snow depth of 10 cm leading to a decrease in 9 lambs per 100 ewes (Figure 5). Fall snow depth explained more variation in lamb-ewe ratios (R^2 = 0.51) than winter or spring depth (R^2 = 0.36-0.40), indicating that conditions inhibiting forage access and movement early in the cold season are of greater importance than snow conditions immediate to or after lambing, in contrast to our previous findings based on range-wide remotely-sensed snow cover (van de Kerk et al. 2018). Thus, integration of remotely-sensed and modeled snow products may be needed to obtain snow properties relevant to wildlife management.

Cosgrove completed SnowModel simulations for 5 other domains with location data from radio-collared sheep in addition to modeling the Wrangells domain. These data include sites within the Brooks Range, Yukon Charley National Preserve, and the White Mountains National Recreation Area, Denali National Park, and Gates of the Arctic National Park. Outputs of these simulations are being prepared for archiving.

Rain-on-snow. In addition to addressing Objective 3, Cosgrove evaluated passive microwave data (NASA MeASURES EASE-Grid 2.0 TB ESDR) for its possibility to detect snow properties important to Dall sheep. We evaluated the performance of an algorithm to detect hard snow layers (Dolant et al. 2018) in heterogeneous alpine terrain such as that used primarily by Dall sheep. The number of hard-snow detections was compared to an index of topographic complexity within our Wrangell St-Elias domain. Initial findings indicate a decrease in detections with increasing topographic complexity at both 18 GHz and 36 GHz frequencies (Figure 6). Further analysis has indicated a strong influence on the frequency of detections by dominant land cover type (as derived from the National Land Cover Database 2011). Cosgrove has presented preliminary results at the 2019 American Association of Geographers Annual Meeting (Cosgrove 2019a) and at the 2019 Western Snow Conference (Cosgrove 2019b). Currently, validation of the detections is being conducted via use of meteorological station data at another site in Alaska, and a manuscript is planned for submission in 2020.

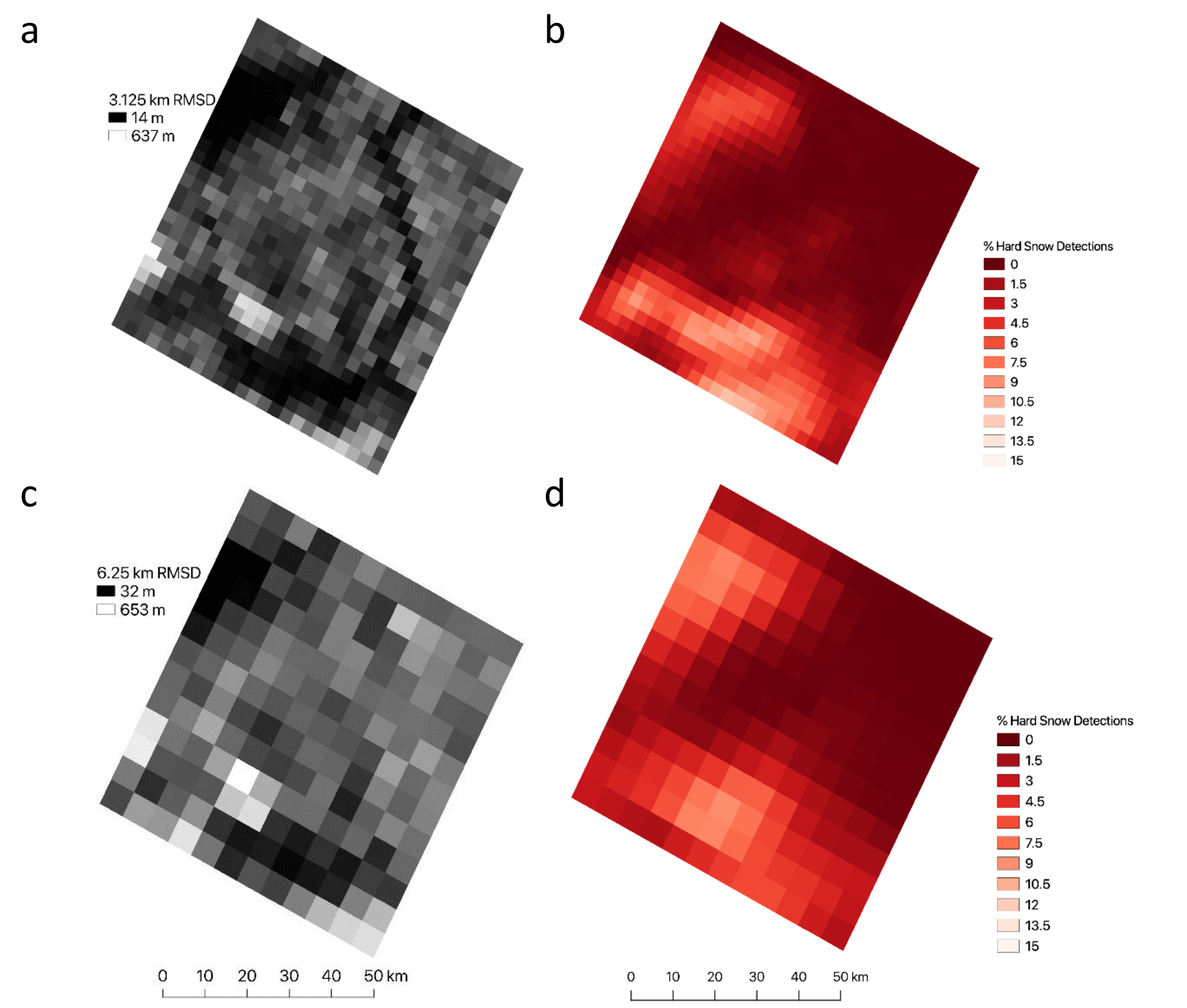

Figure 6. Comparison of the number of hard snow layer detections to topographic complexity for a domain in the Wrangell St Elias National Park and Preserve. The Root Mean Standard Deviation (RMSD) of sub-pixel elevation, as derived from a 5 m IFSAR DEM, is shown in a) and c) for resolutions of 3.125 km and 6.25 km respectively. These resolutions correspond to the 36 GHz and 18 GHz frequencies of the NASA MeASURES EASE-Grid 2.0 TB ESDR (CETB). The number of hard snow detections per pixel at these frequencies are correspondingly shown in b) and d). Detections are calculated from twice-daily CETB data from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) and encompass all days between the 1st October and 1st May for the years 2002 to 2010.

Co-PI Todd Brinkman (University of Alaska Fairbanks)

Co-PI Brinkman supervised undergraduate students Scott Leorna and Gwen Quigley, and Scott continued as a MS student. Brinkman was responsible for Objective 4 (relating our findings to societal implications), with a focus on sheep harvest. Brinkman worked with state (ADFG) and federal agencies (NPS, USFWS) to organize 30+ years of Dall sheep harvest data. Brinkman was a member of the Wildlife and Ecosystem Services working group, and he led several stakeholder engagement activities for this project.

Effect of weather on harvest success. Extensive research has been conducted on the effects of hunting on population dynamics on wildlife, and a growing body of research has assessed factors that influence harvest success. Prior research on harvest success has mainly evaluated the effects of hunter characteristics (e.g., experience level), habitat, and access. Despite decades of the wildlife studies implying that weather conditions influence harvest opportunity, few studies have quantified the impact of weather on harvest success. We assessed the effects of daily weather conditions on harvest success using a long-term dataset on Dall sheep hunter harvests in Alaska (Leorna et al. in review). We compiled daily weather data from mountain regions from August 10 to September 20 between 1999 and 2015. The weather variables in our dataset included daily mean precipitation (cm), relative humidity (%), air temperature (°C), and wind speed (m/s) on a day that sheep harvest occurred. Through a memorandum of agreement with the Alaska Department of Fish and Game (ADF&G), we were provided all individual hunter harvest data between the years 1999 and 2015. We fit generalized linear mixed models to estimate relationships between daily harvest count and weather variables.

Our dataset included 2,287 days when at least one harvest occurred (total harvest of 10,612 sheep) and weather data were available. We found that several weather variables influenced daily success rates. Our best-fit model (Psuedo $R^2 = 0.27$) included year and day of season as random effects (random slopes and intercepts), and temperature, precipitation and relative humidity as fixed effects (Table 2). Daily changes in relative humidity had the largest effect on change in percent daily harvest (Table 2). From highest to lowest effect on daily harvest percent, increased relatively humidity, precipitation, and temperature generally reduced daily harvest rates. For example, a mean (8.2%) increase in RH from one day to the next decreased daily harvest by 11.7%. However, an extreme increase in RH (i.e., 2 SD) from one day to the next decreased daily harvest by 29.5% (Figure 8).

These findings indicate the effects of weather on hunter harvest may be critical to account for to achieve effective harvest management in a shifting climate regime. As seasonal norms in the weather shift, assessing the associations between weather and harvest may provide insight into effective strategies for adapting hunting regulations and meeting harvest goals. To our knowledge, our study is the first to quantify the effects of weather on ungulate harvest.

Table 2. Estimates from best-fitting models for all hunters, only resident hunters, and non-resident hunters with all mountain regions combined of how weather variables affect percent change in daily harvest of Dall sheep in Alaska.

Model	Weather	Coefficient	SE
All Hunters	Temperature (C)	-0.0249	0.0040
	Precipitation (cm)	-0.2617	0.0521
	Wind (m/s)	*Not in best model*	
	Relative Humidity (%)	-0.0152	0.0010
Resident	Temperature (C)	-0.0208	0.0056
	Precipitation (cm)	-0.2662	0.0754
	Wind (m/s)	-0.0515	0.0148
	Relative Humidity (%)	-0.0171	0.0014
Non-Resident	Temperature (C)	-0.0234	0.0071
	Precipitation (cm)	-0.2646	0.0954
	Wind (m/s)	0.0400	0.0174
	Relative Humidity (%)	-0.0114	0.0018

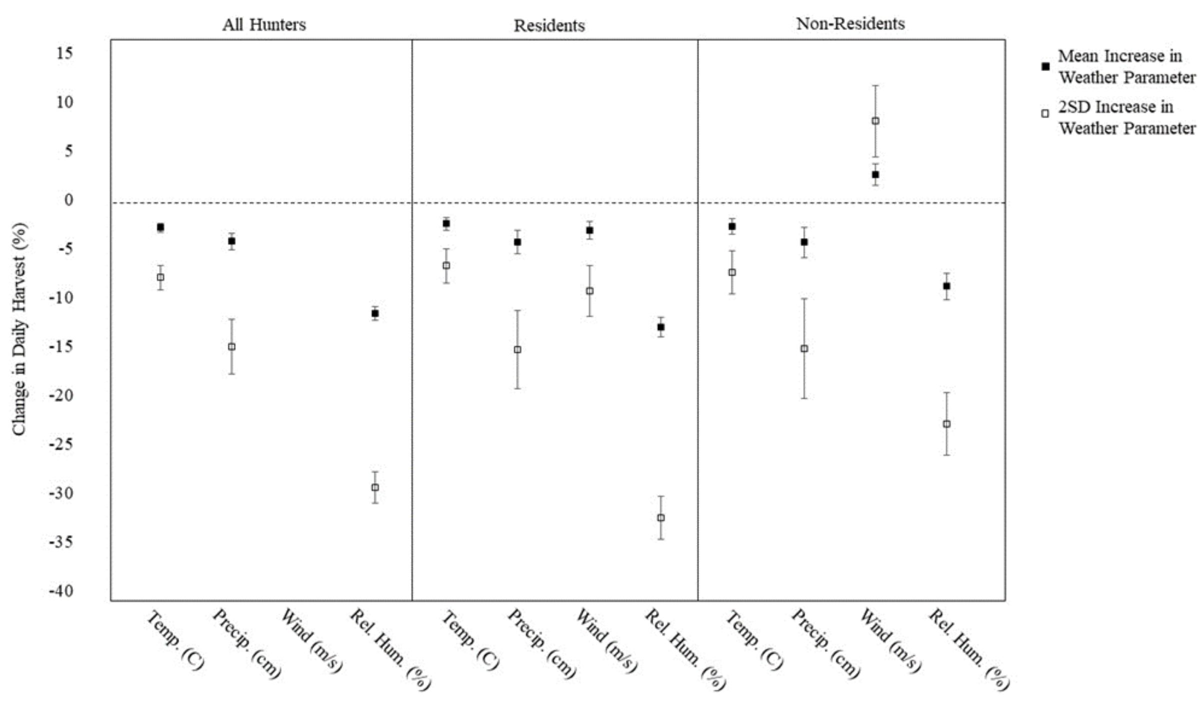

Figure 8. Estimates for all hunter, resident, and non-resident models for how a mean and 2 SD increase in each weather parameter affects percent change in daily Dall sheep harvest in Alaska with all mountain regions combined.

Testing the "ram cliff" hypothesis. Hunter harvest of Dall sheep is largely limited to full-curl rams, which are approximately 6-9 years old (mean = 8 years). Several stakeholder groups (sheep hunters, ADFG) have expressed concern that negative effects of late spring snow cover on lamb survival (van de Kerk et al. 2018) may have a negative effect on sheep hunting opportunities 6-9 years later. The logic behind this concern is that a poor lamb crop may result in fewer full-curl rams 6-9 years later when the lambs should be achieving full-curl thresholds for harvest, which is referred to as the "ram cliff" hypothesis. This hypothesis has never been tested. Therefore, we explored relationships between indices of poor spring weather conditions for lambing and sheep harvest 6-9 years later.

We obtained harvest data and weather data for Game Management Units 20A, 24A, and 25A. Harvest data for GMU subunits were provided by Alaska Department of Fish and Game (ADF&G) through a MOU. Weather data were extracted from The Imiq Hydroclimate Database & Data Portal, a climate data repository created by The Geographic Information Network of Alaska (GINA). Weather data were limited in GMU 25A, which encompasses much of the Eastern Brooks Range. Therefore, GMU 24A and 25A were combined and analyzed as a singular unit.

Annual harvest data from 1983 to 2015 for 20A and 24/25A were used for our analysis. Harvest medians and standard deviations were calculated for each subunit for each harvest scenario (6-9 years later). Weather data, specifically snow depth data, was extracted from The Imiq Data Portal based on location and available date range. None of the available weather stations matched the entire date range of our harvest data. Because of inconsistencies in snow depth data, we averaged data across weather stations to create a more complete picture of spring conditions in the GMU subunit. A total of 5 weather stations in 20A and 10 weather stations in 24/25A were utilized to determine average snow off Julian date. We assessed the relationship between snow-off date and harvest with 6, 7, 8, and 9-year lag scenarios using generalized linear models (GLMs) with Poisson distributions.

We found no correlation between snow-off date and harvest 6-9 years later. None of our GLM models with snow-off date as the predictor outperformed the null model (intercept only). Our findings reject the "ram cliff" hypothesis and suggest variation in harvest is not explained by snow-off date 6-9 years before harvest. Although snow-off date is a good predictor of recruitment, other variables, such as hunter effort, are likely better predictors of actual harvest. Our non-significant findings may help managers address sheep harvest concerns related to annual environmental conditions. However, our analysis was limited by the proximity of weather stations. None of the long-term weather stations were located in alpine environments (sheep habitat). Our MODIS a more accurate description of alpine snow conditions, but these data are only available since 2000, which limits our ability to capture an adequate sample size and variation in both snow-off date and sheep harvest due to the time lags inherent to the analyses. Thus, use of physical modeling (e.g., SnowModel) in conjunction with harvest data may be needed to adequately test this hypothesis.

Stakeholder Engagement. Brinkman led the stakeholder engagement efforts for the team. He attended the annual meeting of the Alaska Chapter of The Wildlife Society (TWS), which was held in Anchorage in March 2018, and in Juneau in March 2019. At the 2019 TWS meeting, a special session was devoted to Dall sheep because of the recent finding and first confirmation of a respiratory pathogen in Alaska's wild sheep population. This pathogen has decimated many wild sheep populations in the continental US. During 2019, Brinkman facilitated discussions on the effects of changing weather conditions on wildlife harvest management. Brinkman is facilitating communication between sheep managers and the ABoVE project to identify ways that our research may assist with agency monitoring and surveillance programs on sheep disease. For example, our project findings on changes in sheep movement and range quality (e.g., shrub expansion) may generate insight into connectivity among subpopulations, thus providing predictions on the potential for disease transfer through mixing and contact.

3) Publications and Products

Peer-reviewed publications

1) Cosgrove, CL, JJ Wells, AW Nolin, J Putera, and LR Prugh. In review. Seasonal influence of snow conditions on Dall sheep productivity in Wrangell-St Elias National Park and Preserve. **PLOS One**.
2) Leorna, S, T Brinkman, J McIntyre, L Prugh, B Wendling. In review. Association between weather and Dall sheep (*Ovis dalli dalli*) harvest success in Alaska. **Wildlife Biology**.
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Scientific Presentations

1) van de Kerk, M, S. Arthur , M Bertram, B Borg, J Herriges, J Lawler, B Mangipane, C Lambert Koizumi, B Wendling, L Prugh. 2019. Remote sensing reveals drivers of Dall sheep survival. **5th NASA ABoVE Science Team Meeting**, La Jolla CA.

2) Cosgrove, CL. 2019a. Can we map hard snow layers in remote mountainous terrain for wildlife applications? Modelling and passive-microwave approaches. **American Association of Geographers** Annual Meeting, Washington DC.
3) Cosgrove, Chris L. 2019b. Mapping hard snow and ice layers in the arctic boreal region: linkages to rain-on-snow events and wildlife. **Western Snow Conference**, Reno, Nevada.
4) Brinkman T, Leorna S, Hasbrouck T, Wendling B. 2019. How might harvest management account for dynamic environmental conditions? **Alaska Chapter of the Wildlife Society** Annual Meeting, Juneau, Alaska.
5) Cosgrove, CL. 2018a. Hostile winters: Are changes in arctic/boreal North America seasonal snow conditions causing Dall sheep population decline? **American Association of Geographers** Annual Meeting, New Orleans, LA.
6) Cosgrove, CL. 2018b. Identifying and mapping hazardous snow conditions for Dall sheep, an iconic North American alpine ungulate, from 1980 to 2017. **MtnClim Conference**, Gothic, CO.
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12) Nolin, AW, EA Sproles, RL Crumley, A Wilson, A Mar, M van de Kerk, and LR Prugh. 2017. Cloud-based computing and applications of new snow metrics for societal benefit. **AGU Fall Meeting**, New Orleans LA.
13) van de Kerk, M, D Verbyla, A Nolin, K Sivy, L Prugh. 2017. Effects of snow extent on Dall sheep recruitment indicate population declines under climate change. **Ecological Society of America Annual Meeting**, Portland OR.
14) Mahoney, P, G Liston, S LaPoint, E Gurarie, B Mangipane, J Jennewein, R Oliver, E Palm, J Eitel, M Hebblewhite, N Boelman, and L Prugh. 2017. Navigating snowscapes: Scale-dependent responses of mountain sheep to snowpack properties. **Ecological Society of America Annual Meeting**, Portland OR.

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17) Cosgrove, C, and A Nolin. 2017. Characterizing mountain snowpack for Dall sheep. **3rd NASA ABoVE Science Team Meeting**, Boulder CO.
18) Nolin, A, R Crumley, E Mar. 2017. Innovations in snow cover mapping for Dall sheep. **3rd NASA ABoVE Science Team Meeting**, Boulder CO.

Outreach and Stakeholder Engagement

1) Project website: http://dallsheep.weebly.com/
2) NASA Earth Observatory "notes from the field" blog entry by L Prugh, 30 May 2018 (https://earthobservatory.nasa.gov/blogs/fromthefield/2018/03/30/wrangell-mountain-expedition/)
3) Prugh, LR. ABoVE Dall sheep project update. Presentation for the Alaska Department of Fish and Game, Fairbanks AK (22 March 2018)
4) Prugh, LR. Dall sheep and snow: linking climate conditions to movement and demography. Presentation as part of the Wrangell Institute for Science and Environment Science Lecture Series, Wrangell-St Elias National Park, AK (13 March 2018)
5) Cosgrove, CL. Up Wait Creek without a pilot. Mountain Sentinels Collaborative Network blog post, 17 Dec 2017 (https://mountainsentinels.org/wait-creek-without-pilot/)
6) Prugh, LR. Feedbacks between climate change and wildlife. Presentation for NASA's Earth to Sky Interpreting Climate Change Workshop, Spokane WA (13 November 2017)
7) Bourgoine, L. Sheep, locals, and wet snow. Protect Our Winters blog entry about the project, 6 June 2017 (https://protectourwinters.org/sheep-locals-wet-snow/)
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9) Friis-Baastad, E. NASA sponsors a closer look at Dall sheep and the warming North. Yukon News article about our project, 23 October 2015 (https://www.yukon-news.com/letters-opinions/nasa-sponsors-a-closer-look-at-dall-sheep-and-the-warming-north/)