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

Year 3 Annual Report (July 2017-June 2018)

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1) Project Summary and 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 is 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?**

We have 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) Year 3 Accomplishments

Activities proposed for Year 3 of this 4-year project consisted of 10 tasks: (1) development of an alpine shrub extent product, (2) SnowModel development/validation, (3) habitat selection modeling, (4) population viability modeling, (5) harvest modeling, (6) snow surveys, (7) supervision and training, (8) stakeholder engagement, (9) meetings and workshops, and (10) manuscript preparation. These activities are shown in the context of our complete project timeline below (Table 1, which is Table 3.4 in the Project Management Plan of our proposal).

Table 1. Dall sheep project timeline.

Activity	Year 1				Year 2				Year 3				Year 4			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Product Development & Modeling																
Compile existing sheep data (*Obj. 2*)		■	■	■												
Develop snow extent & NDVI products (*Obj. 1*)			■	■	■	■										
Develop alpine shrub extent product (*Obj. 1*)					■	■	■	■	■	■	■	■				
Snow model development/validation (*Obj. 3*)					■	■	■	■	■	■	■	■	■	■		
Habitat selection modeling (*Obj. 2*)							■	■	■	■	■	■	■	■		
Population viability modeling (*Obj. 2*)							■	■	■	■	■	■	■	■		
Harvest modeling (*Obj. 4*)											■	■	■	■		
Fieldwork																
Preparation (permits, purchasing)	■	■	■	■												
Sheep captures (*Obj. 2&3*)		■				■										
Snow surveys (*Obj. 3*)						■	■			■	■					
Project Management & Outreach																
Supervision and training	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Stakeholder engagement activities (*Obj. 4*)			■	■	■	■	■	■	■	■	■	■	■	■	■	■
Meetings and workshops		■		■		■		■		■		■		■		■
Manuscript preparation									■	■	■	■	■	■	■	■
Prepare/distribute outreach materials													■	■	■	■

Our study has progressed as largely as planned in Year 3. NDVI products were developed in Year 2 and completed in Year 3. Substantial progress has been made in developing an alpine shrub extent product, and this work will continue into Year 4. Sheep captures were delayed in Year 1 and thus occurred in Years 2 and 3 instead of Years 1 and 2. Habitat selection modeling, harvest modeling, and manuscript preparation are proceeding as planned. Accomplishments led by each PI, co-PI, and key collaborator are described below.

Laura Prugh (University of Washington)

Prugh's activities in Year 3 consisted of fieldwork, supervision of postdoc Madelon van de Kerk and research scientist Kelly Sivy, manuscript preparation, participation in the ABoVE science team, outreach activities, and management the overall project.

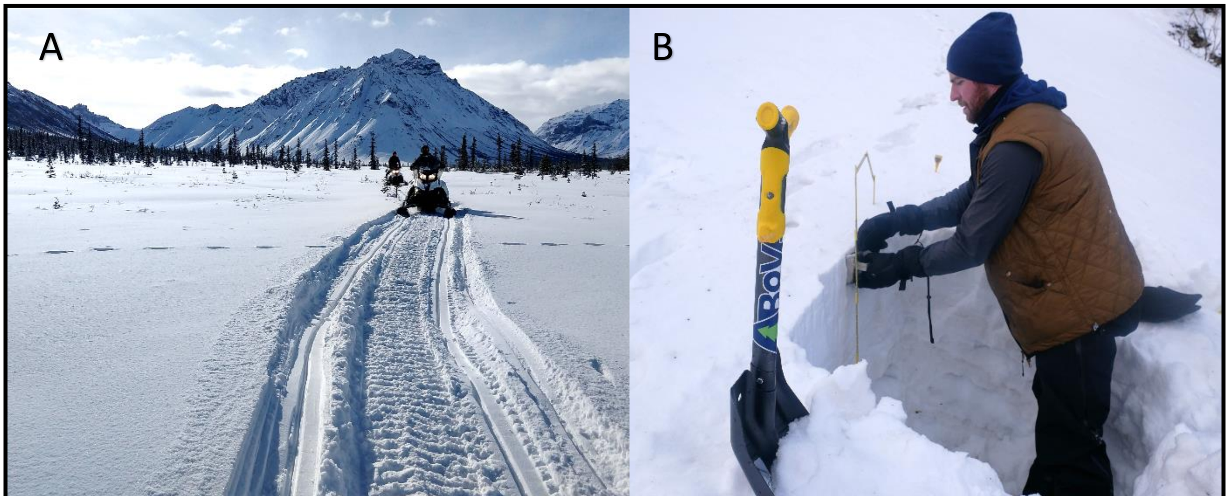

Figure 1. (A) Snowmachining in the study area, and (B) C. Cosgrove measuring snow density and Dall sheep track depths during snow surveys in Wrangell St. Elias National Park, March 2018.

Fieldwork. We conducted three field campaigns in Year 3 in Wrangell St-Elias National Park and Preserve: August 4-7 2017, Sept 14-28, 2017, and March 14-21, 2018 (Figure 1). PhD student Chris Cosgrove (Oregon State University) led the field campaigns, and Prugh was a team member on the March 2018 expedition to conduct snow surveys. 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. Our 22 snow depth stations that we established on Jaeger Mesa the prior year were moved to a new study area during the August and September trips. This move extended the environmental conditions and landscape context of our sampled area, and allowed for winter access via snowmachines. We conducted snow depth transects using a Magnaprobe, dug snow pits at each camera station to record snow stratigraphy, checked cameras at each station, and measured coyote snow track sink depths and associated snow properties. These track measurements were used to determine the snow density threshold for supporting the body mass of a coyote, which is a major predator of Dall sheep. We estimated the density threshold to support the body mass of Dall sheep during last winter's fieldwork as 329 kg/m^3 (Sivy et al. 2018, *Canadian Journal of Zoology*), and the estimated threshold to support a coyote based on this year's data 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.

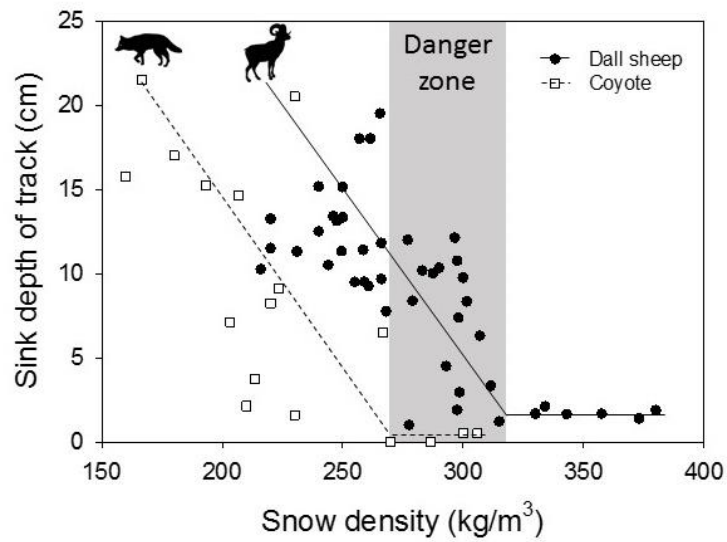

Figure 2. Breakpoint regression was used to find thresholds of snow density for supporting the weight of coyotes and Dall sheep (i.e., densities where snow track sink depths are ~0-2 cm). These thresholds reveal a “danger zone” between 270-329 kg/m^3 where coyotes can run on top of the snow but Dall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

In addition, we calibrated measurements from a simple penetrometer that had been used to measure surface snow compaction in a carnivore study led by Prugh in Denali and nearby areas from 2012-2017. This calibration was successful (R^2 = 0.74), which is exciting because we can now use the 10,539 measurements of snow compaction, snow depth, and snow track sink depth from this study to model the energetics of winter travel for 5 carnivore species, including the two most important predators of Dall sheep, wolves and coyotes. Using SnowModel products validated with MODIS data and our ground observations, we will be able 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.

Supervision and manuscript preparation. Prugh supervised and contributed as a co-author to research that has been published in 4 papers (and associated datasets) in Year 3, and an additional paper that was submitted for publication at the end of Year 3. Kelly Sivy transitioned from a technician to a part-time research scientist under Prugh’s supervision, and she finalized the publication of a peer-reviewed paper resulting from the March 2017 fieldwork (Sivy et al. 2018). Van de Kerk continued her work in the second year of her postdoctoral position with Prugh at UW. She finalized publication of the paper examining effects of spring snow phenology on Dall sheep recruitment (van de Kerk et al. 2018, *Environmental Research Letters*), and she presented the paper at the American Society of Mammalogists meeting in Moscow Idaho in June 2017 and at the Ecological Society of America (ESA) meeting in Portland, OR in August 2017. She also attended the 4th ABoVE Science Team meeting in Seattle this year, and continued to maintain the project website (http://dallsheep.weebly.com/).

Van de Kerk is finalizing a manuscript examining the climatic drivers of Dall sheep survival and cause-specific mortality. GPS and VHF telemetry data from Dall sheep from 1997-2012 were provided by our agency collaborators in 9 areas of Alaska and Canada. 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 number of freeze-thaw events in the previous winter based on satellite measures of radiometric brightness (Figure 3). For lambs, we were also able to identify the underlying mechanism, as predation by coyotes and eagles decreased with increasing NDVI. This study highlights the utility of multiple satellite remote sensing products in understanding how environmental change affects wildlife, because remote sensing products outperformed climatological data in predicting Dall sheep survival. The manuscript will be submitted this summer to the *Journal of Wildlife Management*, which is one of the primary journals used by agency wildlife biologists.

Peter Mahoney, postdoctoral researcher supervised by Prugh on the "Animals on the Move" ABoVE project, led a paper that was a collaborative effort within the Wildlife and Ecosystem Services Working Group (Mahoney et al. in press, *Ecological Applications*). A primary objective of this effort was to evaluate remotely-sensed snow cover (MODIS fractional snow cover) and modeled snow properties (depth and density from SnowModel) as predictors of sheep movements across multiple spatio-temporal scales. 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. Mahoney presented findings from this work at the Ecological Society of America (oral presentation) in Portland, OR and the 4th ABoVE ST meeting (poster) in Seattle, WA. Prugh and van de Kerk also assisted with the paper led by Verbyla (Verbyla et al. 2018, *Remote*

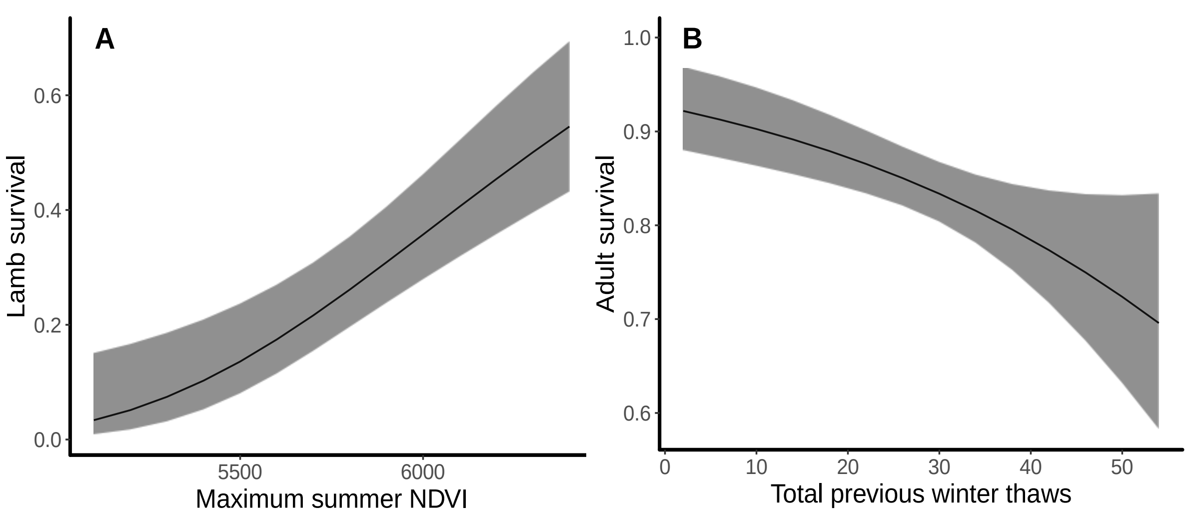

Figure 3. (A) The effect of maximum summer NDVI on Dall sheep lamb survival and (B) the effect of the number of thaws in the previous winter on adult survival.

Sensing), and Prugh and Mahoney contributed to the review paper about snow science and wildlife ecology led by Boelman (Boelman et al. submitted, *ERL*). Prugh presented a talk that synthesized findings from these papers at the AGU ABoVE session in New Orleans.

Science team participation. Prugh participated in the 4th ABoVE Science Team meeting in Seattle. She is an active participant in the Wildlife and Ecosystem Services Working Group and the Stakeholder Engagement Working Group. She provided a slide about the Dall sheep project for Peter Griffith's presentation to Congressman Don Young.

Outreach and stakeholder engagement activities. Prugh conducted several outreach and stakeholder engagement activities in Year 3. 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 Dall sheep project as part of the Wrangell Institute for 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.

Project management. Prugh led teleconferences with the project team to coordinate activities and maintain communication among lab groups and agency collaborators. Meetings occur every other month and have included 14-20 participants. These meetings have been a great way to keep our agency collaborators and one another updated about our activities. She has also kept the project's profile, including the sites and measurements tool, updated on the ABoVE website.

David Verbyla (University of Alaska Fairbanks)

Verbyla's Year 3 activities consisted of manuscript preparation, supervision, and analysis. Verbyla finalized publication of a manuscript in *Remote Sensing*, which presented

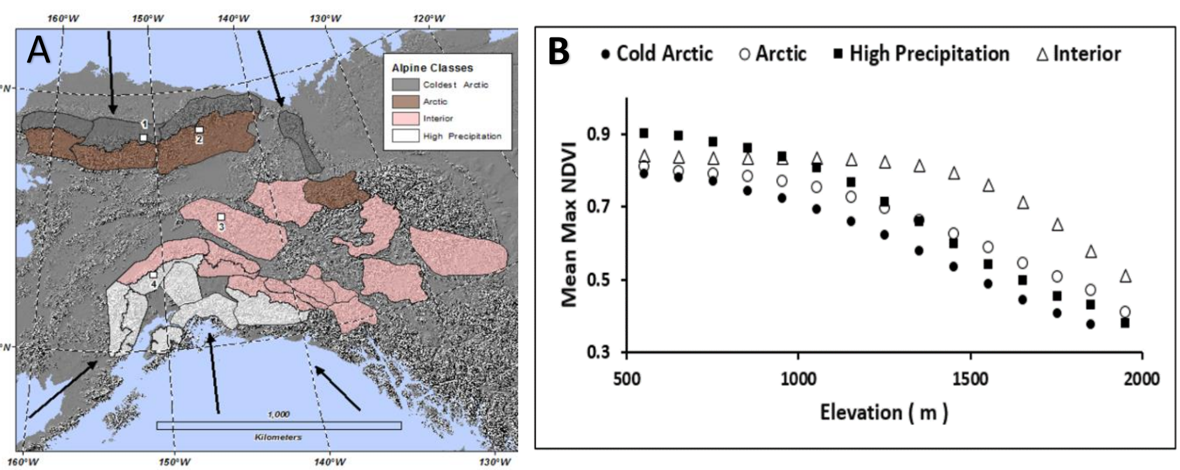

Figure 4. (A) Classification of the 28 mountain units comprising the Dall sheep distribution, and (B) maximum NDVI declines non-linearly with elevation in alpine areas, with the highest NDVI occurring in Interior alpine class sites at higher elevations.

a novel application of MODSCAG to estimate spring snowline elevation each year from 2000-2016 within 28 mountain areas (Verbyla et al. 2018). He also completed analyses using MODIS-based NDVI to examine relationships between regional productivity, temperature, and precipitation that may contribute to spatial variation in the vulnerability and resilience of Dall sheep. Based on regional climatology, the 28 alpine areas were into 4 classes ranging from cold and dry (Coldest Arctic), to warm and dry (Interior), to warm and moist (High Precipitation). Non-alpine arctic tundra studies at several scales have found a linear relationship between remotely sensed maximum NDVI and summer warmth. In our alpine areas, although the lapse rate of summer warmth and elevation was linear, the 2000-2017 maximum NDVI did not decrease linearly as elevation increased (Figure 4). Above 1000 m, the Interior class consistently had the highest NDVI, likely due to colder temperatures and shorter growing season limiting productivity in the other climatic classes. Below 1000 m, the High Precipitation class consistently had the highest NDVI, likely due to moisture limiting productivity in the Interior class at these lower elevations.

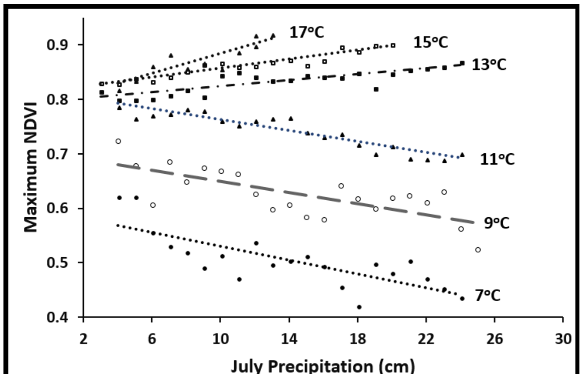

Figure 5. Maximum NDVI increases with summer precipitation in warm alpine areas but decreases with precipitation in cold areas.

Maximum NDVI was positively related to July precipitation in warmer areas, whereas there was a negative relationship between NDVI and precipitation in cooler areas (Figure 5). The positive relationship between NDVI and precipitation in warmer areas became stronger as temperatures warmed from 13 to 17°C. As climate continues to warm, the change in precipitation regime may become more important as a control on alpine vegetation productivity. Verbyla is preparing a manuscript summarizing these findings for submission to *Global Ecology and Biogeography* in summer 2018.

Verbyla is supervising MSc student Mark Melham, who completed his second year at UAF. Melham has finished processing Landsat, AHAP, and NGA imagery that will be used to map shrub expansion in alpine areas, and this analysis will be completed in Year 4.

Verbyla has actively engaged in ABoVE Science Team activities. He is a member of the Vegetation Dynamics and Distribution Working Group and participates in the ASC webinars. He is an active user of the ABoVE Science Cloud.

Anne Nolin (Oregon State University)

Nolin's Year 3 activities consisted of fieldwork, supervision, manuscript preparation, and outreach. Nolin is supervising PhD student Chris Cosgrove, who completed his 2nd year as a PhD student at Oregon State.

Fieldwork. Cosgrove organized and led the removal of all 22 remote cameras from Jaeger Mesa in early August 2017. Approximately 170,000 hourly images of snow depths were remotely acquired in the course of this deployment. After a pause for sheep hunting season, Cosgrove organized and led the field campaign in mid-September 2017 during which the team installed the 22 cameras at a new study area in Pass Creek, ~10km west of Jaeger Mesa. The Pass Creek camera locations were selected to better capture the vegetation transition from boreal forest through low shrub to alpine tundra. Lower-elevation vegetation was under-sampled in the 2016 to 2017 field season, leading to increased uncertainty in SnowModel simulations in this landcover type. To improve this, the Pass Creek sampling scheme was optimized via the development and use of a stratified random sampling algorithm developed by Cosgrove in Python/ArcGIS. Cosgrove wrote a fieldwork blog for the Mountain Sentinels Collaborative Network (https://mountainsentinels.org/wait-creek-without-pilot/).

During the time of maximum snow depth, the accessibility of cameras was tested in March 2018 when Cosgrove and Prugh were joined by two field assistants to conduct detailed snow and animal track surveys. Travelling into Pass Creek from the Nabesna Road by snow machine, the field team greatly appreciated support from NPS employees Morgan Gantz and Luke Wassink who helped navigate and break trail. The ABoVE logistic office helped greatly by supplying an Arctic Oven tent that acted as a base for 6 nights while detailed snow surveys were made by pit measurements of density, temperature and stratigraphy profiles adjacent to 17 of the 22 camera locations. Five cameras were missed due to avalanche precautions in what would prove generally challenging conditions posed by a deeper than average snowpack. Alongside the pit measurements, snow depth transects were measured by using the GPS-enabled Magnaprobe. An Avatech SP2 snow penetrometer was tested to see whether it could resolve potentially important hard layers of snow more efficiently than traditional methods. Cosgrove will return to Pass Creek in July 2018 to lead the retrieval of the cameras with two field assistants.

Research and Manuscript Preparation. Cosgrove completed SnowModel simulations at 100-m, daily resolution from 1980-2017 in 6 domains with location data from radio-collared sheep: Brooks Range, Yukon Charley National Preserve, and the White Mountains National Recreation Area, Denali National Park, Gates of the Arctic National Park, and Wrangell-St Elias (Figure 6A). The time-period of these simulations corresponds to the total temporal extent of the MERRA-2 reanalysis product used as meteorological forcing data in the model. The data from these simulations allow time-series analysis to investigate whether snow conditions within Dall sheep ranges are exhibiting directional shifts due to climate change.

Focusing initially on the Wrangell St Elias, where SnowModel has been calibrated using the in-situ field observations from the 2016-2017 field season, no statistically significant trends in snow cover were found from 1980-2017. Examination of lamb to ewe ratios, however, revealed a positive relationship between recruitment success and a metric describing the percentage area where forage is more accessible (Figure 6B). 'Forageable Area' is defined as the percentage area above shrubline where snow depth is beneath mean Dall sheep chest height (<54 cm) and the critical snow density threshold (<329 kg/m^3) discovered in our field measurements of track sinking depths in Year 2 (Sivy et al. 2018).

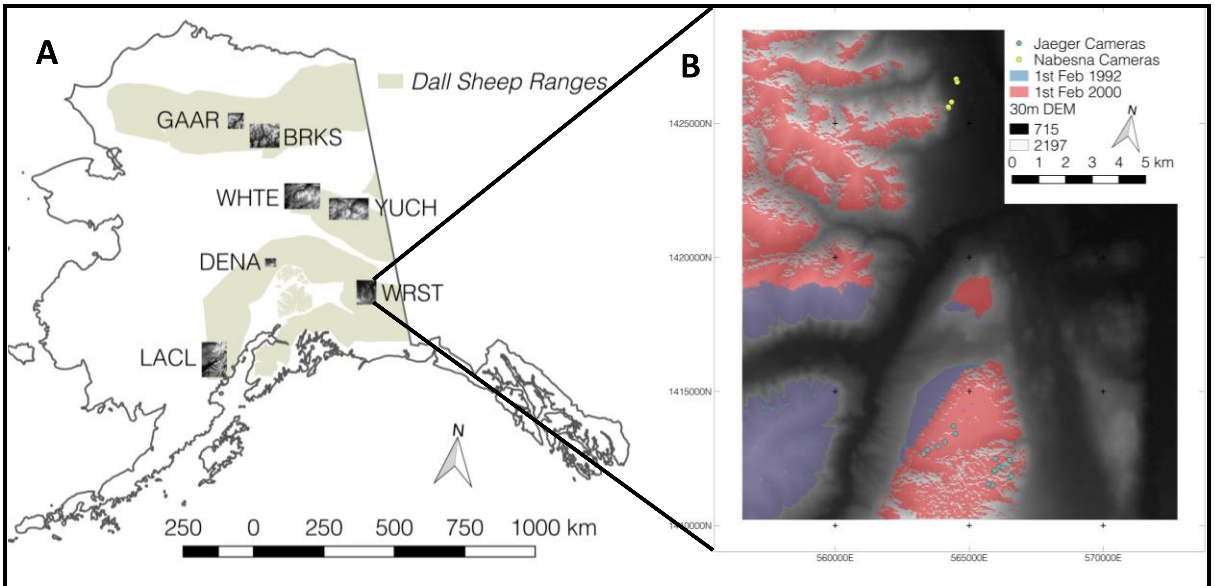

Figure 6. (A) SnowModel domains (black to white DEMs) and Dall sheep ranges in Alaska. GAAR = Gates of the Arctic National Park and Preserve, BRKS = Brooks Range, WHTE = White Mountains National Recreation Area, YUCH = Yukon-Charley Rivers National Preserve, DENA = Denali National Park, WRST = Wrangell St Elias National Park, and LACL = Lake Clark National Park and Preserve. (B) SnowModel-derived Forageable Area (see text) shown for the Jacksina Park Unit in WRST on 1 Feb 1992 (blue), 1 Feb 2000 (red), and both dates (purple). Snow depth camera stations are shown. The 1992 lamb-to-ewe ratio was below average (0.1697 lambs per ewe), whereas 2000 saw higher recruitment (0.3780 lambs per ewe).

This finding supports van de Kerk et al.'s (2018) results on the importance of the snow disappearance date to recruitment success and Mahoney et al.'s (in press) analysis of habitat selection behavior. Cosgrove is leading the preparation of a manuscript on this work. He presented findings in a poster at the 4th ABoVE Science Team meeting in Seattle and a talk at the American Association of Geographers Annual Meeting in New Orleans in April 2018. Extending the analysis to the other SnowModel domains is ongoing.

Using the remote camera images from both field seasons, Cosgrove has developed an image analysis algorithm that automatically reads the snow depth from the demarcated snow stakes in each image. Data from these images were implemented in the calibration and validation of SnowModel. To overcome issues with slight camera movement during deployment, the object detection package in Google's Tensorflow platform was utilized and explored as a means to detect Dall sheep in the images. Cosgrove is currently exploring other approaches georeferencing the viewshed of images to map snow-free areas.

In support of work using the NASA MeASURES EASE-Grid 2.0 TB ESDR (an enhanced resolution passive- microwave product – see https://nsidc.org/pmesdr/) to detect rain-on-snow events and ice-layers within the snowpack, Cosgrove attended the Snow Microwave Radiative Transfer (SMRT) Modelling workshop in Col du Lautaret, France in February of 2018.

Nolin's team submitted a manuscript to a special issue of *Remote Sensing* on Google Earth Engine in Earth science applications (Crumley et al. submitted, *Remote Sensing*). The manuscript describes the snow cover products developed by her team using Google Earth Engine that have been used in several of the Dall sheep project publications. She presented a talk about these metrics and their application to Dall sheep management at the AGU meeting in December 2017.

Science team participation. Cosgrove attended the ABoVE Science Team Meeting in January 2018, presenting a poster. He has shared remote camera data with Jonathan Wang (Woodcock, NNX15AU63A) for validation of landcover maps, and Nolin and Cosgrove contributed to a publication led by Natalie Boelman (Boelman et al. submitted, *ERL*). Nolin is serving as liaison between ABoVE and the SnowEx project. SnowEx is funded by NASA Terrestrial Hydrology Program. Nolin is funded as a PI on a SnowEx project to examine snow-forest interactions. There is significant interest in a joint ABoVE-SnowEx airborne science campaign in 2020. It is anticipated that ABoVE will provide data for snow-off conditions and SnowEx investigators will provide ground-based and airborne snow-on data during March and later. Discussions are still in early phase. Nolin has been in discussions with both the SnowEx and ABoVE leadership, and she is lead author on a white paper that describes potential advantages to SnowEx for such a campaign.

Todd Brinkman (University of Alaska Fairbanks)

Brinkman's Year 3 activities consisted of supervision, stakeholder engagement, and manuscript preparation. Brinkman is supervising Scott Leorna, who started as an undergraduate student in Year 1 and became a MSc student in Fall 2016. Brinkman and Leorna are examining the association between weather and Dall sheep harvest success in Alaska. Leorna obtained sheep harvest data from our ADFG collaborators, which went back to 1984. He then compiled daily data from 522 weather stations across sheep range. Relationships between weather data (e.g., wind, precipitation, humidity, temp) and daily harvest success were modeled across Alaska and within individual mountain ranges for different groups of hunters (resident/nonresident, airplane/non-airplane transport, and guided/nonguided). We found that increases in precipitation and wind speed were the two weather variables having the largest negative impact on sheep harvest success. For example, a 1 unit (km/s) increase in wind speed decreased daily sheep harvest by approximately 6%. Wind was more likely to affect guided hunters than non-guided hunters, whereas precipitation was more likely to affect non-guided than guided hunters. As expected, wind was also more likely to affect hunters that used airplanes to access their hunting areas. Quantifying the effects of weather on sheep harvest is important for two main reasons: 1) Climate-related effects on harvest success of game has not been quantified; 2) Dall sheep hunting is one of the most contentious wildlife management issues in Alaska, and additional information on factors that affect hunting opportunities is urgently needed to address hunter conflict.

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. At the 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 lower 48. 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.

Glen Liston (Interworks Consulting, Inc.)

In Year 3, Liston implemented a new version of SnowTran-3D that improved the model simulation of snow in alpine and Arctic landscapes where blowing snow imposes important controls on the snow distribution. He also developed a new snow-trafficability model and implemented the ability to assimilate snow density observations in SnowModel/SnowAssim. He contributed to the "snowscapes" manuscripts led by Mahoney and Boelman, and worked with Cosgrove to improve his SnowModel simulations of Dall sheep habitat.

Janet Rachlow (University of Idaho)

Rachlow is a key collaborator funded by a contract with the National Park Service to model habitat selection by Dall sheep. Rachlow and her team (Jocelyn Aycrigg, Adam Wells, and Oz Garton) have completed an analysis of seasonal habitat selection by adult females in Lake Clark National Park and Preserve. These analyses evaluated strength of four ecological factors (security, thermal shelter, energy expenditure associated with movement, and forage) in shaping selection across the lambing period, summer, and winter seasons. Model predictor variables included a suite of vegetative, climatic and terrain covariates, including output from a snow model projection conducted with Glen Liston and the NASA Dall sheep team. A manuscript presenting results of the habitat modeling for Lake Clark is currently being drafted for submission during summer 2018.

3) Year 4 Objectives

Prugh will continue to organize team conference calls, participate in the ABoVE Science Team, and provide general oversight for the project. Prugh and van de Kerk will submit the Dall sheep survival analysis for publication. They will prepare and submit an additional paper that synthesizes project findings and examines how changing snow and vegetation conditions affect Dall sheep population viability. Prugh will also lead the preparation of outreach materials that summarize findings for stakeholder groups.

Verbyla and Melham will focus on using historic and current Landsat imagery to locate areas of potential shrub expansion across a climate gradient of alpine areas. They will then use historic aerial photography and current NGA imagery to validate these shrub expansion areas in the alpine.

Nolin will continue as liaison for the ABoVE-SnowEx joint airborne science campaign anticipated for spring 2020. She will be presenting up-to-date information at an AGU Town Hall meeting for SnowEx in December 2018. Cosgrove will complete Phase 1 fieldwork by removing all remote camera installations in July 2018. He will use the snow depth data from the images and data from the March 2018 field campaign to further improve SnowModel's simulations of high-latitude mountain areas. Cosgrove will extend his analysis comparing lamb-to-ewe ratios to seasonal snow metrics to 5 additional domains and examine the 1980 to 2017 time-series of each for potential trends and increased frequency of extreme snow conditions. Continuation of the remote camera image analysis approaches and rain-on-snow/ice-layer mapping is anticipated to lead to publication of results in summer 2019. Cosgrove plans to attend and present at the MtnClim conference in September 2018, the American Geophysical Union Annual Meeting in December 2018 and at the American Association of Geographers Annual Meeting in April 2019.

Brinkman and Leorna will submit their study on the relationships between weather and sheep harvest for publication. Brinkman will also test for associations between recent Project findings (snow characteristics, range quality, population size) on sheep hunting opportunities (success and effort), and potentially, viewing opportunities. They hypothesize that large fluctuations in annual snow characteristics (especially late spring snow conditions) will be reflected in sheep harvest data. Sheep population declines, particularly those resulting from low lamb survival, will be reflected in the sheep harvest data approximately 6-8 years after the low survival year. The time lag is a result of the full-curl harvest regulation.

Liston will continue to advise Cosgrove in running SnowModel, and he will contribute to publications.

Rachlow and the U Idaho team have completed habitat selection by Dall sheep in other regions, including Denali National Park and Preserve, Gates of the Arctic National Park and Preserve, the Brooks Range, and Yukon-Charley Rivers National Preserve. On-going analyses are underway for Dall sheep in the White Mountains. They will complete a manuscript comparing and contrasting results of habitat selection across regions during 2018-19. This work will include an exploration of how to project habitat selection into the future under climate change scenarios to evaluate predicted changes in distribution and abundance of suitable habitat for Dall sheep. They will continue coordinating with the project team to integrate habitat selection analyses into broader project goals.

4) Changes

Our plans in Year 3 did not deviate from our proposal; tasks are being completed according to or ahead of schedule.

5) Year 3 Publications and Products

Peer-reviewed publications

1) Crumley, RL, AW Nolin, EA Sproles, and EG Mar. Submitted. SnowCloudMetrics: Snow information for everyone. **Remote Sensing**.
2) Boelman, N, G Liston, E Gurarie, A Meddens, P Mahoney, P Kirchner, G Bohrer, T Brinkman, C Cosgrove, J Eitel, M Hebblewhite, J Kimball, S LaPoint, A Nolin, S Højlund Pedersen, L Prugh, A Reinking, L Vierling. Submitted. Integrating snow science and wildlife ecology in Arctic-boreal North America. **Environmental Research Letters**.
3) PJ Mahoney , GE Liston, S LaPoint, E Gurarie, B Mangipane, AG Wells, TJ Brinkman, JUH Eitel, M Hebblewhite, AW Nolin, N Boelman, and LR Prugh. In press. Navigating snowscapes: scale-dependent responses of mountain sheep to snowpack properties. **Ecological Applications**.
4) van de Kerk, M, D Verbyla, AW Nolin, KJ Sivy and LR Prugh. 2018. Range-wide variation in the effect of spring snow phenology on Dall sheep population dynamics. **Environmental Research Letters** https://doi.org/10.1088/1748-9326/aace64.
5) Sivy, KJ, A Nolin, C Cosgrove, LR Prugh. 2018. Critical snow density threshold for Dall sheep (*Ovis dalli dalli*). **Canadian Journal of Zoology** https://doi.org/10.1139/cjz-2017-0259.
6) Verbyla, D, T Hegel, A Nolin, M van de Kerk, T Kurkowski, L Prugh. 2017. Remote sensing of alpine spring snowline in Dall sheep mountain ranges of Alaska and western Canada. **Remote Sensing** 9:1157 https://doi.org/10.3390/rs9111157.

Published Datasets

1) Verbyla, D. Submitted. ABoVE:16-Year Maximum NDVI Northern Alaska and Yukon Territory. ORNL DAAC, Oak Ridge, Tennessee, USA.
2) Van de Kerk, M, D Verbyla, AW Nolin, KJ Sivy, and LR Prugh. Submitted. ABoVE: Range-wide Dall sheep lamb-to-ewe ratios and environmental covariates, 2000-2015. ORNL DAAC, Oak Ridge, Tennessee, USA.
3) Mahoney, P, G Liston, B Mangipane, and LR Prugh. 2018. ABoVE: Responses of Dall Sheep to Snowpack Properties, AK, 2005-2008. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1602
4) Sivy, KJ, AW Nolin, CL Cosgrove, and LR Prugh. 2018. ABoVE: Dall Sheep Track Sinking Depths, Snow Depth, Hardness, and Density, 2017. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1583

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Scientific Presentations

1) Prugh, LR, D Verbyla, M van de Kerk, P Mahoney, KJ Sivy, G Liston, A Nolin. 2017. Snowscape ecology: linking snow properties to wildlife movements and demography. **AGU Fall Meeting**, New Orleans LA (oral presentation).
2) 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 (oral presentation).
3) 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 (oral presentation).
4) 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 (oral presentation).
5) Cosgrove, C, and A Nolin. 2018. Snowpack variability and Dall sheep recruitment. **4th NASA ABoVE Science Team Meeting**, Seattle WA (poster presentation).
6) Mahoney, P, G Liston, S LaPoint, E Gurarie, B Mangipane, A Wells, T Brinkman, J Eitel, M Hebblewhite, A Nolin, N Boelman, L Prugh. 2018. Navigating snowscapes: scale-dependent responses of mountain sheep to snowpack properties. **4th NASA ABoVE Science Team Meeting**, Seattle WA (poster presentation).

Outreach and Stakeholder Engagement

1) Project website: http://dallsheep.weebly.com/
2) Mountain Sentinels Collaborative Network blog post by C Cosgrove, 17 Dec 2017 (https://mountainsentinels.org/wait-creek-without-pilot/)
3) 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/)
4) Prugh, LR. ABoVE Dall sheep project update. Presentation for the Alaska Department of Fish and Game, Fairbanks AK (22 March 2018)
5) 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)
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)