

CONNECTING ALASKA LANDSCAPES INTO THE FUTURE

Results from an interagency climate modeling,
land management and conservation project

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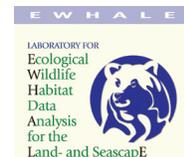
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Chuck Young, USF&WS

Executive Summary

The Connecting Alaska Landscapes into the Future project (Connectivity Project) was a collaborative proof-of-concept effort that used selected species to identify areas of Alaska that may become important in maintaining landscape-level connectivity, given climate change. Project results and data presented in this preliminary report are intended to serve as a framework for research and planning by stakeholders with an interest in ecosystem conditions that may change and an interest in ecological and socioeconomic sustainability.

The Connectivity Project was co-led by Karen Murphy and John Morton from the U.S. Fish and Wildlife Service (USFWS), Nancy Fresco from the University of Alaska (UA) statewide Scenarios Network for Alaska Planning (SNAP), and Falk Huettmann from the University of Alaska Fairbanks (UAF) Ecological Wildlife Habitat Data Analysis for the Land and Seascape Laboratory (EWHALE) lab. The project included a series of three workshops conducted in 2008 and 2009, with participants from state and federal agencies and non-profit organizations.

Using climate projection data from SNAP and input from project leaders and participants, we modeled projected changes in statewide biomes and potential habitat for four species selected by the group. The primary models used were SNAP climate models based on downscaled global projections, which provided baseline climate data and future projections; Random Forests™, which we used to match current climate-biome relationships with future ones; and Marxan software, which we used for examining landscape linkages.

The Connectivity Project modeled projected shifts in broadly categorized species assemblages (biomes) based on existing land cover, current climatic conditions, and projected climate change. The Alaska biomes used in this project (Arctic, Western Tundra, Alaska Boreal, Boreal Transition, North Pacific Maritime, and Aleutian Islands) were adapted from the unified ecoregions of Alaska (Nowacki et al. 2001). Because climate change may introduce new biomes into the state, we also considered six western Canadian ecozones. We used Random Forests™ to model projected spatial shifts in potential biomes, based on SNAP projections for mean temperature and precipitation for June and December for the decades 2000–2009, 2030–2039, 2060–2069, and 2090–2099, which defines three time steps for modeling connectivity from potential ecological change.

While it should be noted that “potential biomes” (species assemblages that might be expected to occur based on linkages with prevailing climate conditions) are not the same

as actual biomes, results suggest that approximately 60% of Alaska is anticipated to experience a geographic shift of present biomes during the twenty-first century. Our initial models predict that by the end of the century, the Arctic and the Alaska Boreal will each diminish by approximately 69% and Western Tundra, by 54%—all but disappearing in its original location—in favor of the Montane Cordillera and Boreal Transition. In addition, much of southeast Alaska may be in the process of shifting from North Pacific Maritime to Canadian Pacific Maritime—again, as constrained by functional barriers. Western Tundra may be the most vulnerable biome, with the least resilience for conservation purposes even without considering the potential for significant loss due to sea level rise.

To assess connectivity (defined as the degree to which existing biomes are linked to their future potential locations), we identified areas that the models predicted would remain part of the same biome over the course of this century, and defined these areas as possible refugia. We identified areas of very high and very low Normalized Difference Vegetation Index (NDVI), as proxy measures of biodiversity and endemism for the proof-of-concept modeling, without the constraint of ecological mechanisms that might influence the rate of biome or species distribution change between time steps. We resampled climate forecasts from 2 km to 5 km resolution and used Marxan to assign connectivity scores based on status as refugia and NDVI values. Finally, we sketched in connections between areas that ranked highest. To the best of our knowledge, this is the first time that linkages have been developed based on both spatial and temporal analyses.

The Connectivity Project also examined potential impacts on four selected species: barren-ground caribou (*Rangifer tarandus granti*), Alaska marmots (*Marmota broweri*), trumpeter swans (*Cygnus buccinator*), and reed canary grass (*Phalaris arundinacea*). The Alaska marmot model incorporated terrain roughness (based on digital elevation model) and predicted severe decreases in the potential range of this species, a Beringia relict, although further information is needed on its ecology and distribution. Reed canary grass, an invasive exotic, is projected to continue its spread along river and road systems as climate warms and road networks grow, and may spread rapidly in the Seward Peninsula. Trumpeter swans are expected to move westward and northward as their preferred boreal habitat shifts. Modeling caribou distributions proved problematic because of their broad ecological plasticity, but it helped to elucidate new avenues for future research.

Based on our preliminary results, we recommend re-running models with broader data inputs; validation of our forecasts with field studies to document causal mechanisms; seeking further input from researchers and land managers, including Native Corporations and villages; repeating these analyses using more detailed land-cover maps; and modeling additional species.

Introduction

Scope and Purpose of the Report

The Connecting Alaska Landscapes into the Future project (Connectivity Project) was a complex partner-driven, consensus-driven effort. Our goals were to:

- Identify lands and waters in Alaska that likely serve as landscape-level migration corridors for shifts in species distribution currently and into the future given climate change; and
- Identify conservation strategies with our partners that will help maintain landscape-level connectivity by focusing conservation efforts, minimizing redundant research and monitoring efforts, and sharing data and information for these areas.

The results are intended to serve as a framework for a planning tool for land managers, wildlife managers, local planners, nonprofits, and businesses with an interest in future ecosystem conditions, sustainability, and landscape-level conservation. Data presented in this report are preliminary and are not intended to be prescriptive, but rather to serve as a guide for planning and as a starting point for synergy and further research.

Terms and Definitions

The following terms, used throughout the report, are defined as follows:

Biodiversity: Biodiversity refers to a composite measure of both species' richness (total number of species) and evenness (relative abundance of all species).

Biome: A biome is a broadly defined species assemblage. For the purposes of this project, Alaska biomes were based on those defined by Nowacki et al. (2001), and Canadian biomes were based on ecozones defined by Environment Canada. Biomes are defined in detail in Appendix C.

Climate envelope: A climate envelope is the range of conditions (in this study, mean temperatures and precipitation during June and December) in which a biome, or species, is most likely to occur, based on past climate data and current biomes.

Connectivity: For this project, connectivity is the degree to which existing biomes are linked to their future potential locations, as defined by the best fit with projected future climate data.

Conservation: Conservation is characterized by land use in which the goal of maintaining ecosystem function predominates over large-scale resource extraction or landscape alterations by humans. However, in the face of climate change, conservation may not mean maintenance of the status quo, but rather successful adaptation to changing conditions.

Corridor: A corridor is an unbroken connection between habitat patches for a species or species assemblage, allowing for either seasonal migration or dispersal

Ecoregion: An ecoregion is a smaller and more precisely defined region within an ecozone. Canadian climate data for this project were available at the level of mean historical values for ecoregions.

Ecozone: An ecozone is a Canadian region broadly defined by dominant vegetation and geophysical attributes. In this project, ecozones were considered as similar to Alaska biomes (see Appendix C).

NDVI: Normalized Difference Vegetation Index (NDVI) is a numerical index that indicates the greenness of a satellite image by comparing the reflection of photosynthetically active radiation and near-infrared radiation. NDVI can be used as a proxy measure for landscape productivity.

Novel biome: This term is used to describe future conditions, where a potential biome exists in a location outside of the current distribution for that biome.

Potential biome: A potential biome is the biome that best matches projected future climate conditions for a region, based on the linkage between past climate and existing biomes. Potential biomes may differ from actual future biomes for a number of reasons, including differences in soil type and hydrology, or lag time between climate change and seed dispersal and other mechanisms of ecosystem change.

Refugia: Refugia are areas in which the potential future biome is projected to be the same as the existing biome through all time steps from 2000 to 2100.

Resilience: In general, resilience is the ability to avoid irreversible change despite ongoing perturbations. In this report, resilience is used as a measure of the ability of a region to remain within the broad climate envelope that defined its biome over the course of this century.

Project Background

Understanding how climate change will affect our ability to sustain biodiversity and traditional subsistence into the future is a common challenge faced by federal, state, Native, and private land managers interested in conserving Alaska's natural resources for future generations. Identifying lands that would allow a shift in distribution of renewable resources and their continued sustainable use will help prioritize future conservation efforts. These important areas for connectivity can then be considered in conjunction with ongoing statewide, national, and international conservation initiatives (e.g., the Alaska Comprehensive Wildlife Conservation Plan, Yukon to Yellowstone Conservation Initiative, Western Boreal Conservation Initiative, and Conservation of Arctic Flora and Fauna).

Work began in 2008 with the establishment of a North and West Alaska Cooperative Ecosystem Studies Unit (CESU) agreement between USFWS and researchers from SNAP and EWHALE. Scenarios Network for Alaska Planning is a statewide research group that creates and interprets projections of climate change based on downscaled global models. Its goals are to apply new or existing research results to meet stakeholders' requests for specific information, provide timely access to scenarios of future conditions in Alaska for more effective planning, and communicate information and assumptions to stakeholders. The EWHALE lab in UAF's Institute of Arctic Biology, Biology and Wildlife Department, specializes in spatial modeling of landscapes and populations for conservation planning and analysis.

The Connectivity Project was co-led by Karen Murphy and John Morton from USFWS, Nancy Fresco from SNAP, and Falk Huettmann from EWHALE. The project included three workshops in 2008 and 2009, with participants from state, federal, and non-profit agencies (Appendix A). The first workshop allowed participants to understand the overall question and underlying data, and jointly refine the goals of the project. At the second workshop, preliminary modeling results were discussed, and suggestions were made for changes and improvements. At the final workshop, participants helped define the final outputs of the project, including this report and its data and deliverables.

Between workshops, project leaders and participants conducted a literature review to assess similar and related projects from the U.S., Canada, and other regions (Appendix B). Preliminary models were developed and presented at the workshops for review and refinement.

To define future connectivity, we gathered data on existing conditions and linked these to models of future conditions. To assess connectivity at the statewide level, we developed a structured framework process for modeling future species distributions and connectivity, with both reactive and anticipatory adaptation approaches in mind. Using downscaled climate projection data from SNAP, and input from project leaders and participants, Dr. Huettmann created statistical models explicit in space and time for projected changes in statewide biomes that represent potential habitat for key species identified by the group. With feedback from project leaders and participants, he refined these models and used them as the basis for creating maps of potential future statewide connectivity by use of Marxan (Ardon and Possingham 2008) and other methods.

All results presented in this report are based on data that were available during 2008 and 2009. Models can be powerful tools, and can be invaluable when used to deal with situations where no direct data are available for wide areas, such as projection of future conditions in Alaska and parts of western Canada. However, it should always be remembered that uncertainty is inherent in all modeling efforts and that models are updated toward better predictions. Whenever possible, we have attempted to include the best available models and data and define both the type and magnitude of uncertainty in our results. Relevant and documented data products are available for an assessment of our modeling forecasts, which in turn require biological validation with field trials in a separate process.

Through this project, we identified modeling opportunities that are available to create decision tools, and learned by trial and error about the strengths and weaknesses of the straightforward and sometimes simple modeling methods that were employed. In this report, we identify the lessons learned and highlight areas where further research or improved data would enhance these models.

Models Used in the Connectivity Project

MODELING CLIMATE CHANGE: SNAP CLIMATE MODELS

Scenarios Network for Alaska Planning (SNAP) climate projections are based on downscaled regional Global Circulation Models (GCMs) from the Intergovernmental Panel on Climate Change (IPCC). The IPCC used fifteen different GCMs when preparing its Fourth Assessment Report released in 2007. SNAP analyzed how well each model predicted monthly mean values for three different climate variables over four overlapping northern regions for the period from 1958 to 2000. Model selection and downscaling methods are described in Walsh et al. 2008. For this project, we used mean (composite) outputs from the five models that provided the most accurate overall results (see Technical Addendum I). We relied primarily on model runs based on midrange (A1B) predictions of greenhouse gas emissions, as defined by the IPCC. It is important to note that the more pessimistic A2 scenario or even more severe scenarios are now considered likely, given recent climate and emission trends (Nakicenovic et al. 2001, Raupach et al. 2007). The GCM results were scaled down from 2.5° latitude/longitude blocks to 2 km resolution, using data from Alaskan weather stations and PRISM (Parameter-elevation Regressions on Independent Slopes Model). PRISM uses point data, a digital elevation model, and other spatial data sets to generate gridded estimates of monthly, yearly, and event-based climatic parameters, such as precipitation, temperature, and dew point (Walsh et al. 2008). SNAP models have been assessed using backcasting (<http://www.snap.uaf.edu/downloads/validating-snap-climate-models>) and comparison to historical conditions, and have proven to be robust in predicting overall climate trends.

In this first iteration, exploring the relationship between climate and land cover, we used climate data for June and December in order to capture estimates of seasonal

climatology across Alaska. Clearly, the selection of different months of data to incorporate into the models would produce differing results, and a full application, using all 12 months of data to determine which are the greatest drivers, would be required in a robust application of these models.

For further information on SNAP data and SNAP models, please see www.snap.uaf.edu.

MODELING CLIMATE CHANGE ENVELOPES: RANDOM FORESTS™

We employed the Random Forests™ modeling algorithm to identify probable relationships between historic temperature and precipitation data and known distributions for species and biomes across Alaska. These relationships were then used to predict future species and biome distribution based on projected temperature and precipitation. This approach, known as ensemble modeling, takes the average of the outputs of multiple individual models, thus generally providing more robust predictions (Breiman 1998, 2001). More specifically, Random Forests™ (http://www.stat.berkeley.edu/~breiman/RandomForests/cc_home.htm) represents an averaged collection of independent, optimized Classification and Regression Trees (CARTs). This technique is used successfully in pattern recognition, in data mining, and for predictions (Hegel et al. 2010). The Tree/CART family of models, including Random Forests™, uses optimized binary recursive partitioning to calculate the best fit of each data point. Random Forests™ employs the concept of “bagging,” based on a subsample (columns and rows) of the data, where multiple trees are created for each of those data sets and each tree is grown on about 63% of the original training data, due to the bootstrap sampling process chosen. Thus, 37% of the data are available to test any single tree, which allows Random Forests™ to be self-calibrating and avoids over-fitting. Because its calculations are fast, multivariate, and programmable, Random Forests™ is convenient to use and tends to provide a better fit than linear algorithms and similar methods. Random Forests™ deals well with interactions between predictive variables, intrinsically accounting for their relative power, and ranks predictors (Breiman 2001; Hegel et al. 2010). This modeling algorithm also does well when handling “noisy” data, that is, data with high intrinsic variability or missing values (Craig and Huettmann 2008). The model algorithm, which is widely used and well tested, has previously been applied to climate change research and other studies (Climate Change Atlas 2010, Lawler 2001).

MODELING CONNECTIVITY: MARXAN

We used the Marxan model (Moilanen et al. 2009) to evaluate which regions of the state are likely to be most important in the coming decades for conservation of functioning biomes, based on our identification of areas that may be biome refugia and areas with potentially high endemism or potentially high productivity.

Marxan uses multiple interactive geographic information system (GIS) layers to provide output, based on user-defined requirements (targets and penalties). Marxan was created to aid systematic reserve design and prioritization, for conservation planning. The

model uses stochastic optimization routines based on simulated annealing, a technique in which the model attempts to satisfy all requirements in a multivariate spatial context by approaching more optimal solutions stepwise, using a cost-benefit approach with weighted factors. Although Marxan's algorithms do not generate a single ideal solution to a given optimization problem, the model can generate recommendations for spatial reserve systems that achieve particular biodiversity-representation goals with high mathematical optimality. Marxan is a commonly used model for prioritizing conservation areas.

Important Factors and Models That Were NOT Incorporated

SEA LEVEL RISE

Alaska is expected to see significant change associated with rising sea levels over the next century. Unfortunately, despite local attempts, there is no statewide sea level rise model available for Alaska at this time. Over the next century, global sea levels are projected to rise between 0.6–1.9 feet (the range of estimates across all the IPCC scenarios) (IPCC 2007). However, in some localities of southeast and southcentral Alaska, the land surface is actually rising as a result of the retreat and loss of glacial ice (isostatic rebound) and, secondarily, as a result of active tectonic deformation. Creating a sea level rise model first requires both improved digital elevation models and improved coastline maps. Because coastal areas are likely to experience change associated with ocean waters as well as potential shifts in climate, the preliminary results presented in this report should be viewed as conservative representations of change along coastal Alaska.

PERMAFROST CHANGE

Permafrost is one of the primary ecosystem drivers for much of Alaska. Researchers, as well as everyday Alaska residents, have been documenting changes in permafrost stability in recent decades. SNAP, in collaboration with Dr. Vladimir Romanovsky and Dr. Sergei Marchenko of the UAF Geophysical Institute, is currently revising the permafrost map for Alaska. They are also creating a predictive model of how permafrost responds to climate changes, including an assessment of permafrost temperatures at varying depths statewide throughout the period spanned by SNAP data. Once this model is completed, it could be incorporated into the process described by the Connectivity Project to improve the ecological representation for potential biome shifts and refugia. In this report, we refer to refugia as areas that are expected to have more stable climatic patterns through the next century.

ALFRESCO

Boreal ALFRESCO (Alaska Frame-based Ecosystem Code) was developed by Dr. Scott Rupp at UAF. The model simulates the timing and location of fire disturbance and the timing of vegetation transitions in response to fire. Climate variables are among the key drivers of ALFRESCO. Thus, when SNAP climate projections are used as inputs,

ALFRESCO can be used to create projections in changes in fire dynamics with changing climate. ALFRESCO operates on an annual time step, in a landscape composed of 1×1 km pixels. The model currently simulates four major subarctic/boreal ecosystem types: upland tundra, black spruce forest, white spruce forest, and deciduous forest.

For further information on the ALFRESCO model, see Rupp et al. (2000) in Appendix B: Additional Reading and References and http://jfsp.nifc.gov/documents/ALFRESCO_UGuide_ver03.pdf.

Part I **Modeling Shifts in Ecosystem/Vegetation**

Landscape Classification

To provide a landscape-level approach to connectivity, we modeled projected shifts in potential ecosystem type (biomes) based on existing land cover, current climatic conditions, and projected climate change. Biomes provide a good “container” for biological units of a landscape. The biomes used were based on the unified ecoregions of Alaska (Nowacki et al. 2001). We also defined an additional biome, the Alpine biome, based on elevation and latitude. It should be noted that Alpine is a special biome, because it is linked (“anchored”) specifically to higher altitudes and thus cannot move freely across the landscape as boreal forest can, for instance. Due to limited statewide data on where alpine vegetation occurs, our model proved unreliable, and we did not use this biome in any of our analyses (Technical Addendum II: Identifying the Alpine Biome).

Future projections are based on potential climate-linked conditions, and do not take into account mechanistic biological explanations such as ease of seed dispersal or species migration. Projections are based solely upon mean summer (June) and winter (December) temperature and precipitation to characterize the range in site-specific climate throughout the year. However, these are powerful and parsimonious indicators, because many variables associated with vegetation type, land cover, and altitude are covariates with temperature and precipitation. For example, the presence or absence of permafrost, the depth of the active layer, hydrologic conditions, potential evapotranspiration, growing season length, and fire frequency are all strongly linked to climate. Thus, these variables can be expected to change as climate changes, although lag times might differ. While using climate data alone worked well in Random Forests™, we are fully aware that reality is more complex. In many cases, due to the interactions of geophysical and ecological variables, true landscape change may be more extreme or less extreme than that predicted by our models.

Alaska’s ecosystems and vegetation have been classified in many different ways, including fine-scale maps of vegetation types and more broadly defined biomes. We considered several options, including the unified ecoregions defined by Nowacki et al. (2001); the

LANDFIRE classification scheme; The Nature Conservancy (TNC) biomes; and National Land Cover Data (NLCD) maps from the United States Geological Survey (USGS).

The LANDFIRE data were not yet complete for Alaska, although we did use drafts from two mapping units—70 and 71—to test the applicability of these data for this project (Technical Addendum III: LANDFIRE Mapping of Units 70 and 71). The Nature Conservancy biomes (Gonzalez et al. 2005), created for the North American continent, were deemed to have unrealistic classifications for part of the state. National Land Cover Data land cover definitions were sometimes too broad and ill-defined, relying on classifications such as “all coniferous” rather than identifying dominant species that change with latitude. Thus, the group decided to focus on the Nowacki ecoregions, with some minor modifications (Figure 1).

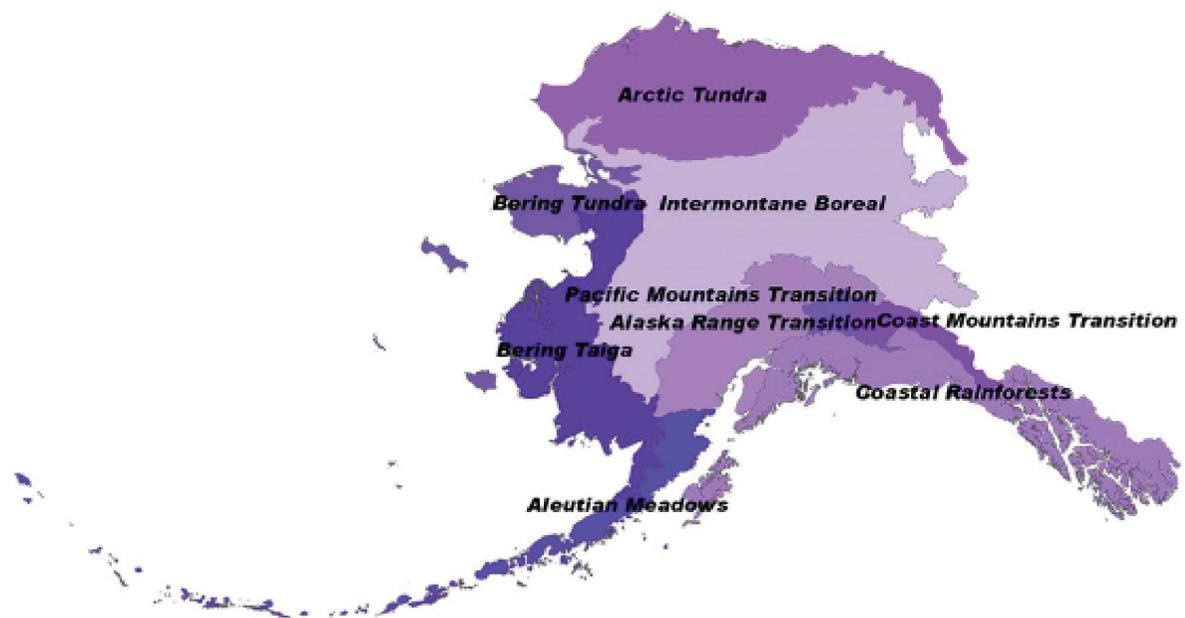


Figure 1 – Ecological groups, as defined by Nowacki et al. (2001). See Appendix C for full descriptions of each biome.

The Nowacki classification for Alaska includes nine groups within three broad categories. Based on these groups, we made some combinations and added the Alpine category to yield seven biomes defined by their dominant vegetation and topography: Alpine, Arctic, Western Tundra, Alaska Boreal, Boreal Transition, North Pacific Maritime, and Aleutian Islands (Appendix C).

Since climate and vegetation are not constrained by political boundaries, model data included biomes from nearby regions of Canada that may shift into Alaska from the south and east because of changing climate. This inclusion required an estimation of regions similar in scale and resolution to the six Alaska biomes. We used Canadian ecozones for this



Figure 2 – Alaska biomes and Canadian ecoregions. Twelve ecological zones were classified using past climate data, allowing Canadian vegetation groups to shift into Alaska in model runs depicting future conditions. See Appendix C for full descriptions of each biome and ecoregion.

purpose (Figure 2). Ecozones, which are defined in a manner similar to biomes (<http://www.ec.gc.ca/soer-ree/English/Framework/NarDesc/>), are based on spatial differences in a combination of landscape characteristics. For the purposes of this modeling exercise, we considered six ecozones: Montane Cordillera, Taiga Cordillera, Boreal Cordillera, Taiga Plains, Boreal Plains, and Pacific Maritime (Appendix C). It should be noted that some Canadian ecozones have significant overlap with Alaska biomes.

Modeling the Effects of Climate Change on Biomes

We used Random Forests™ to model projected spatial shift in potential biomes for three future periods. Our methods are summarized below, and a detailed description of the methodology used is provided in Technical Addendum IV: Defining Biomes and Modeling Biome Shifts in Random Forests™.

Climate data inputs were all based on the midrange (A1B) emissions scenario for SNAP’s Composite GCM, and included mean monthly temperature and precipitation for the months of June and December for the decades 2000–2009, 2030–2039, 2060–2069, and 2090–2099, which define three time steps in the twenty-first century. Using decadal rather than annual data tends to smooth the interannual variability that occurs in both the real world and in SNAP models, and thus constrains variation in model output, where mean values are of more interest than variability is for our purposes. Using decadal means tends to smooth out the “outer edges” of the climate data and the ranges, leading to underestimates of the potential variability.

In our early model runs, we used only Alaska biomes. The group decided, however,

that our results would be more ecologically defensible if we allowed for shifts across the international boundary with Canada. Thus, our final runs all used twelve land classifications, including the six Alaska biomes and the six Canadian ecozones described above, which allows for Canadian biomes to enter Alaska if the models find them to be better matches for future climate conditions.

Random Forests™ used the closest available approximation of existing conditions as training data. For Alaska, this meant using SNAP model outputs for the current decade, 2000–2009 (note that these data are simulated, and not directly linked to weather station data). Simulated, rather than actual, climate data were used to represent existing conditions in part because actual data for the 2000–2009 decade were not yet available during the modeling for this project in 2008 and 2009. Each 2 km grid cell on the statewide map was defined by four parameters (in addition to biome): mean decadal June temperature and precipitation, mean decadal December temperature precipitation (Figure 3). For the Canadian ecoregions, we used climate normals available from Government Canada (based on 1971–2000 weather station data) for each ecozone within the larger ecoregions (NCDIA 2009). To normalize the map resolution for purposes of using the Random Forests™ model and to match the temperature and precipitation data that we used for Alaska, we assigned each 2 km grid cell within each Canadian ecozone and used the climate data for the applicable ecoregion. For further information on the linking of Canadian and Alaskan data, see Technical Addendum IV.

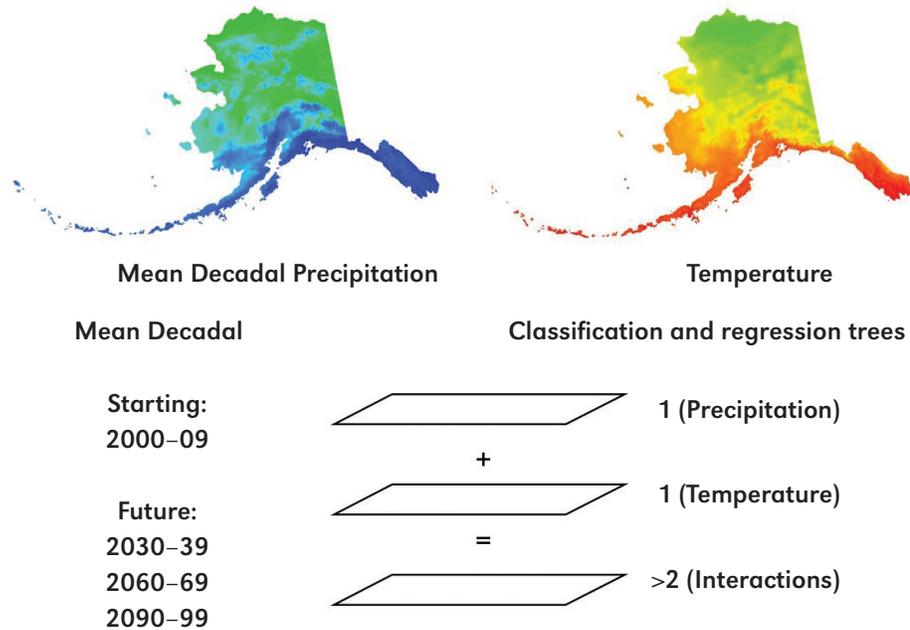


Figure 3 – Conceptual illustration of how the Random Forests™ model was used to create climate envelopes for different modeling subjects. Mean decadal temperature and precipitation data were taken from the Composite A1B climate model for the 2000–2009 decade to define the framework for predicting climate envelopes used in the future. Random Forests™ incorporates interactions in addition to the additive values from each layer included in the model.

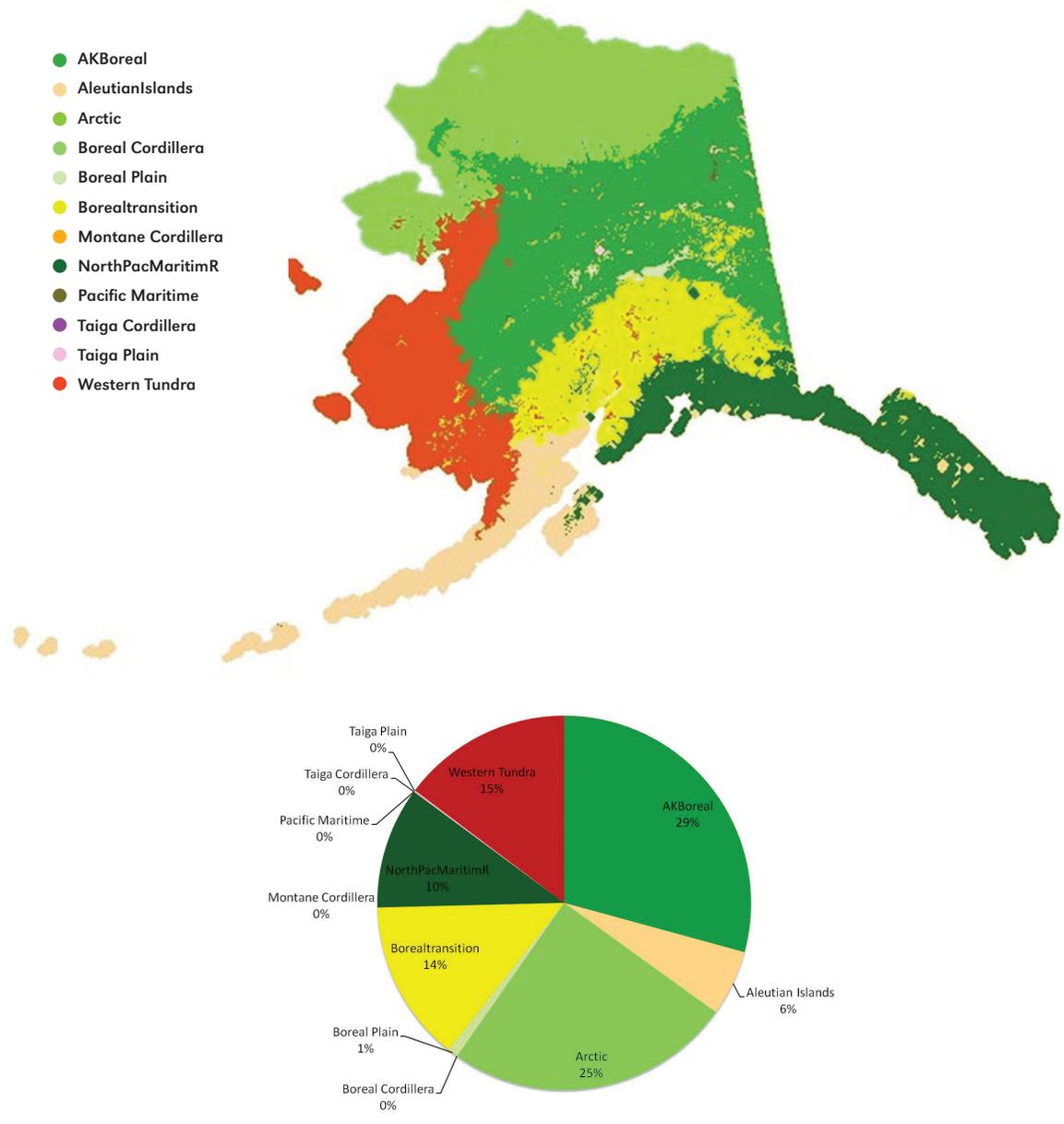


Figure 4 – Current biome types as predicted by SNAP climate data. This map shows the best fit for each 2 km pixel in Alaska for 2000–2009 climate projection data, based on climate envelopes for pre-defined biomes and ecoregions in Alaska and Canada.

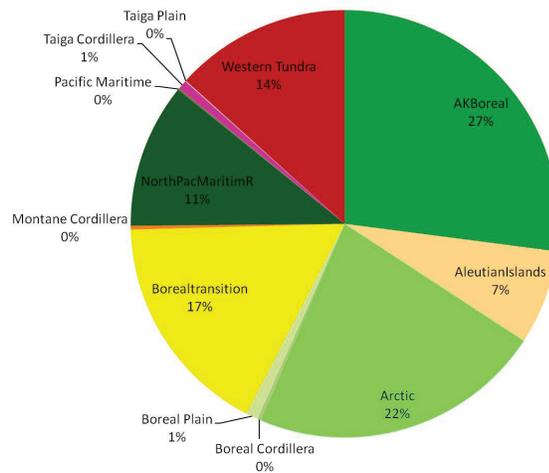
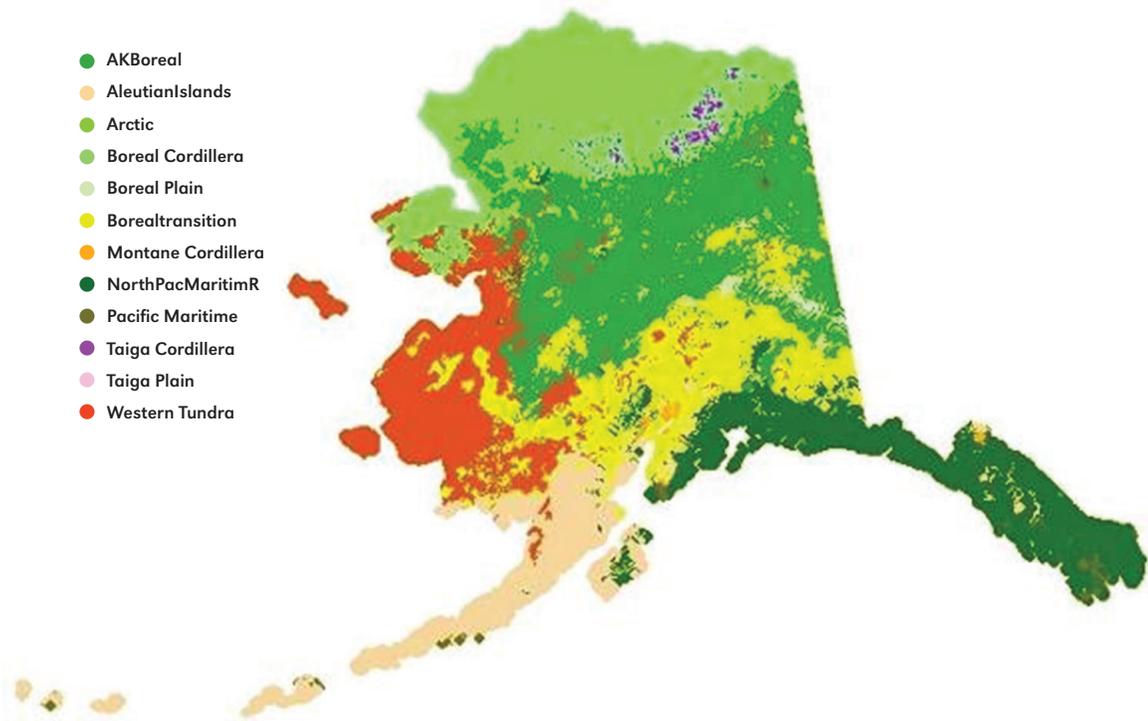


Figure 5 – Projected potential biomes for 2030–2039. The Boreal Transition biome is encroaching northward and westward, and the Arctic biome has started to shrink with Taiga Cordillera coming from the east.

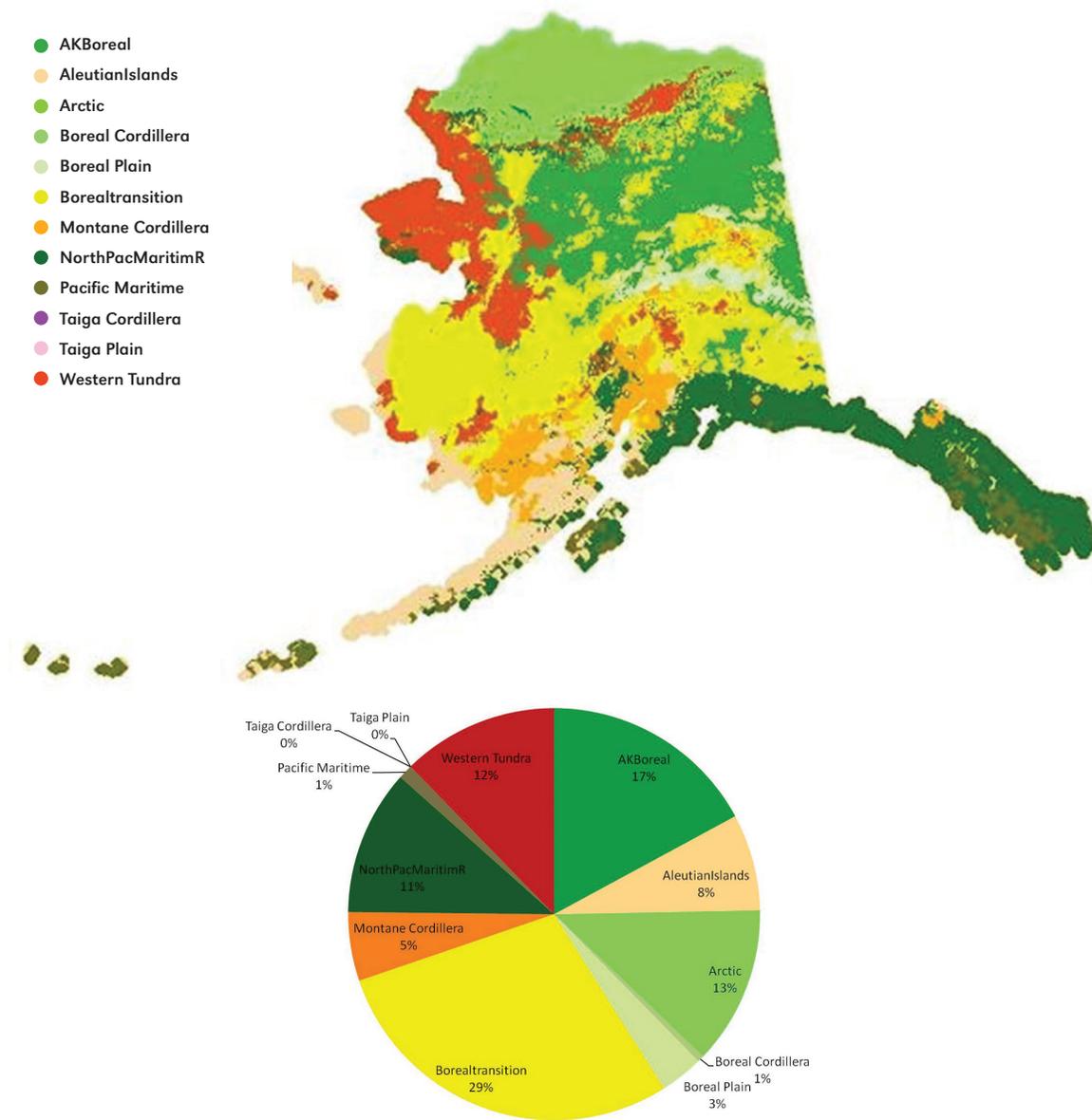


Figure 6 – Projected potential biomes for 2060–2069. Marked northward shifts are now observed, with some Canadian biomes moving in from the east. Note that although Montane Cordillera appears in broad regions of western Alaska, this is likely a potential rather than an actual change; it would be difficult for the species of this ecoregion to effect such a large spatial shift in this time step, or to undergo such a large change in physiography.

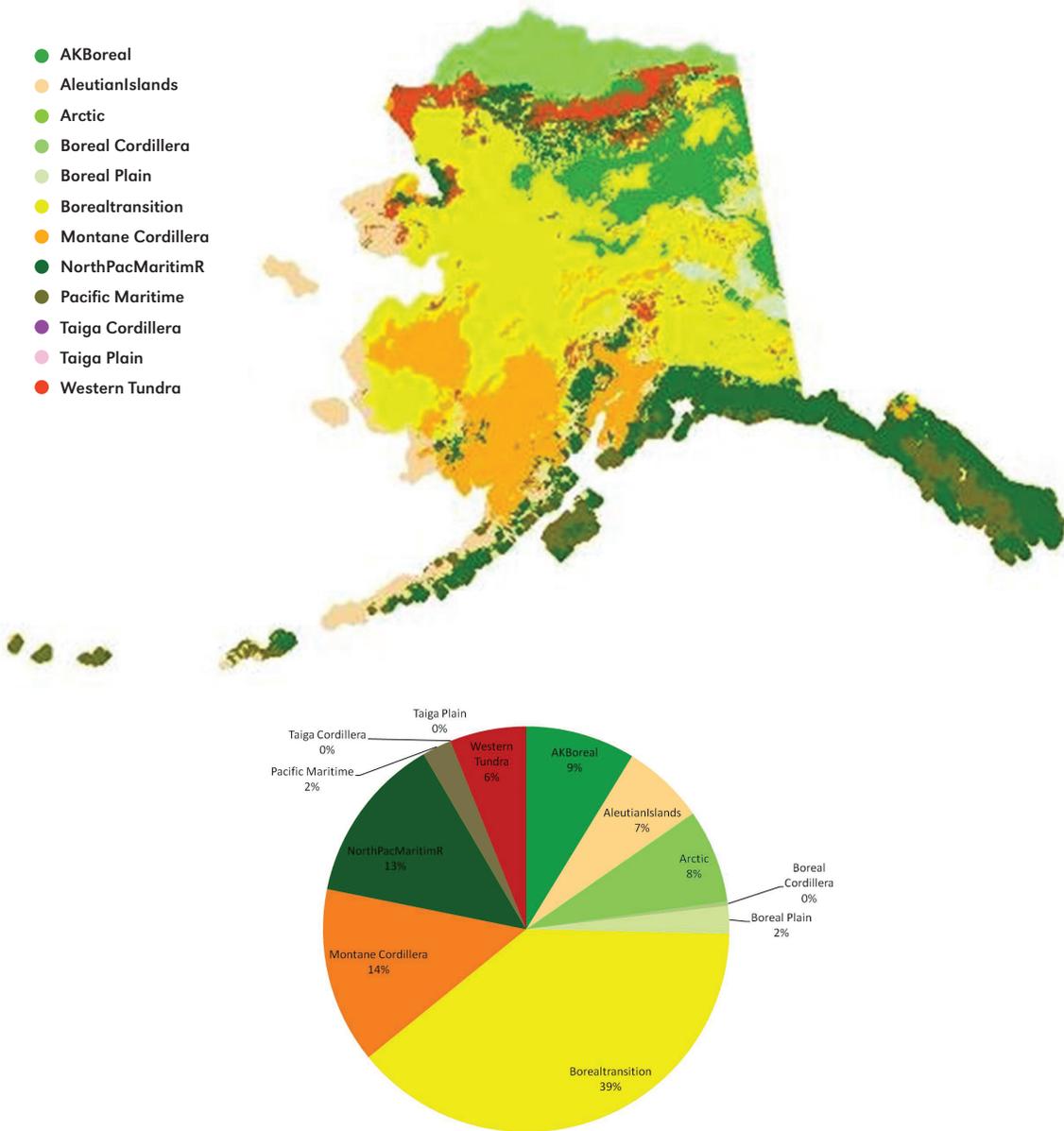


Figure 7 – Projected potential biomes for 2090–2099. The Arctic, Alaska Boreal, and Western Tundra biomes are all greatly diminished, in favor of the Montane Cordillera and Boreal Transition. In addition, nearly half of southeast Alaska has shifted from North Pacific Maritime to the Canadian Pacific Maritime.

Random Forests™ used simultaneous analyses of these data to define the current climate envelope of each biome. Climate envelopes are the range of climate conditions that describe the current distribution for each biome. We used the modeled GCM data for the current decade 2000–2009 to define the current climate envelope for each biome’s distribution. We created a 5 km lattice of all climate data (resampling from the original 2 km resolution) to make our data sets more manageable in size. The model then determined which biome climate envelope was the best fit for each set of projected future climatic conditions. The model output was a new map for each decade, depicting potential biome shift based on the best climatic envelope fit for each grid cell (Figures 4–7). Note that the map of the current decade (Figure 4) redefines biomes and ecoregions under current climate conditions to show slight existing irregularities in the delineation of biomes.

As shown in Figure 8, some biomes and ecoregions have temperature envelopes that

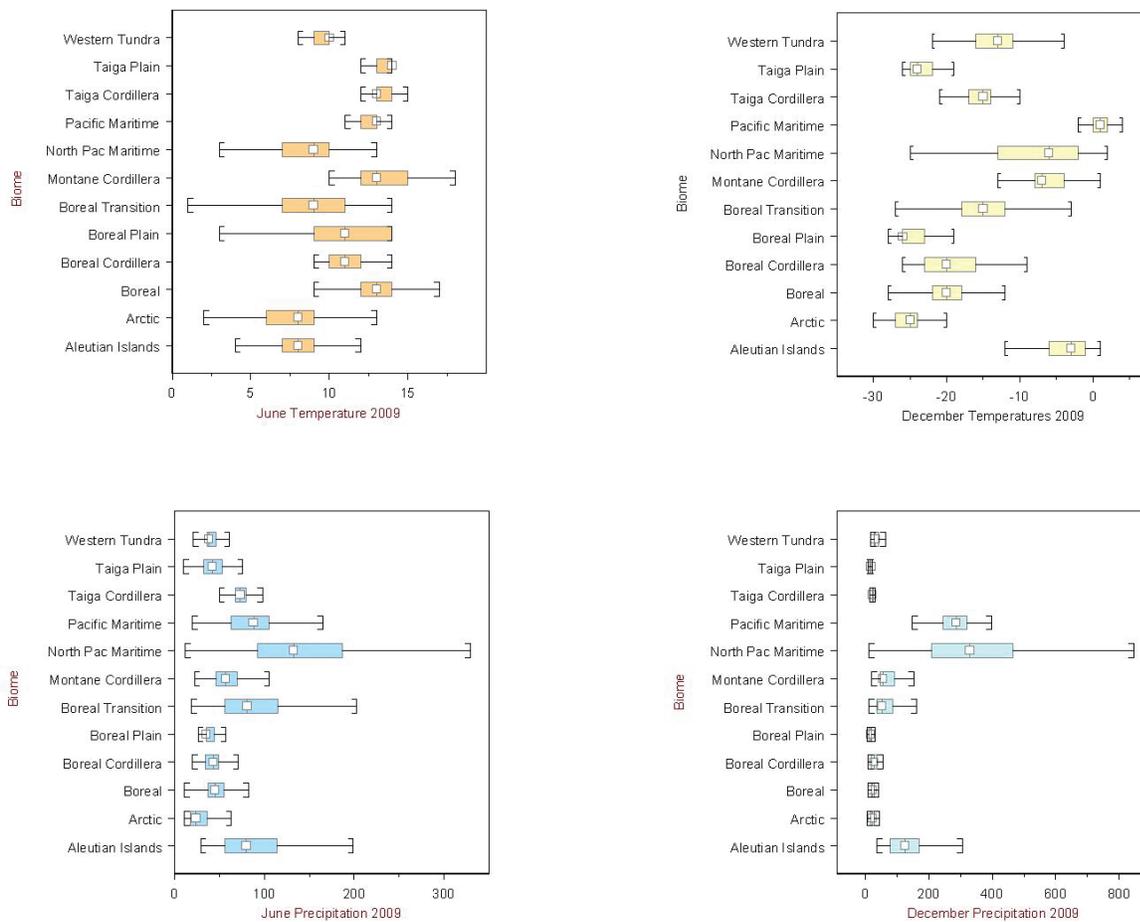


Figure 8 – Box plots comparing climate envelopes for biomes/ecoregions. Each plot shows mean values, one standard deviation, and maximum and minimum values for one model input. Units are millimeters of precipitation and degrees Celsius. Note that the smaller ranges for Canadian ecoregions are indicative of the fact that these data sets were at much coarser resolution than Alaska data sets. Max and min values far from the mean often represent mountainous zones or other “non-typical” outliers within the region.

are similar to others, while some biomes and ecoregions appear to be more distinct. This disparity in variability is important to note on two levels: First, it demonstrates that slight differences in climate are associated with radically different ecosystems (e.g., grassland in the Aleutian Islands vs. coastal rainforest in the North Pacific Maritime of southeast Alaska), and that climate might not be the only parsimonious factor to determine biomes. Second, it outlines an important avenue for future research: an assessment of the similarities and differences between Canadian ecozones (e.g., Boreal Cordillera) and Alaska biomes (e.g., Alaska Boreal) that might be expected to have similar climates. Thus, some zones might be effectively combined or repartitioned in future model iterations. Such repartitioning would have ramifications in our assessment of biome refugia, landscape resilience, and landscape connectivity, as described later in this report. Why would changing (repartitioning) the initial boundaries of biomes change the results from the models? Climate envelopes are derived based on climate variables and interactions across a defined geographic area. If that geographic area is changed, the climate envelope is likely to change too. That change is carried forward into the results, as the “new” climate envelopes is matched with the modeled climate data across Alaska.

Results show marked shifts in potential biomes, with the boreal and arctic zones shifting northward and diminishing in size. By 2039, our model projects that the Boreal Transition biome climate envelope will encroach northward and westward, and the Arctic biome will shrink by 10%. By 2069, projections indicate marked northward shifts, almost complete change in western coastal regions, and some Canadian biomes moving in from the east. It is important to note that these shifts represent **potential** rather than actual biome shift, since in many cases it is unconfirmed that seed dispersal, soil formation, and other functional changes could occur at the same rate as climate change. For example, although Montane Cordillera appears in broad regions of western Alaska, it would be difficult for the species of this ecoregion to effect such a large spatial shift in the modeled time step. These models illustrate that the climate envelope of today’s Montane Cordillera better matches the future climate of places in western Alaska than any of the climate envelopes that describe the biomes that exist in Alaska today.

Our initial models predict that by the end of the century, the Arctic and the Alaska Boreal will each diminish by approximately 69% and Western Tundra, by 54%—all but disappearing in its original location—in favor of the Montane Cordillera and Boreal Transition. In addition, much of southeast Alaska may be in the process of shifting from North Pacific Maritime to Canadian Pacific Maritime—again, as constrained by functional barriers. The model suggests that two-thirds of Alaska will experience a potential biome shift in climate this century, although shifts are occurring at temporally and spatially different rates across the landscape. Even without sea level rise, Western Tundra may be the rarest and least protected biome within the next century, with less than 2% remaining unchanged by 2100. Not surprisingly, the three most southern biomes (Boreal Transition, Aleutian Islands, and North Pacific Maritime) were the only biomes with climate envelopes that occur in greater distribution through the next century.

As noted before, potential biomes are not the same as actual biomes, and these results

are based on only two months (June and December) of climate data. A full assessment of potential biome shifts should be done, using additional months as well as secondary data, such as soil depth and permafrost, before results are used for landscape planning. Nevertheless, our models indicate that large-scale change is likely by the end of the century. Further assessment should confirm the broad trends shown here. As will be examined and discussed in the following sections, when these changes are assessed within a conservation framework, they will pose new opportunities and challenges for land managers.

Part II

Connectivity, Resilience, and Conservation Potential

To assess landscape-level connectivity, we needed to determine what regions of the state are likely to be most important in coming decades for the conservation of functioning biomes. We then needed to ascertain how well these habitat areas may be protected (based on existing conservation land status) and connected (based on corridors and landscape proximity). We decided to model connectivity by focusing on areas identified as biome refugia and areas with potentially high endemism or potentially high productivity. We then examined how these areas might be linked over the course of this century across the cumulative potential range of each biome within that time period, given constraints on the amount of land in conservation status (Figure 9).

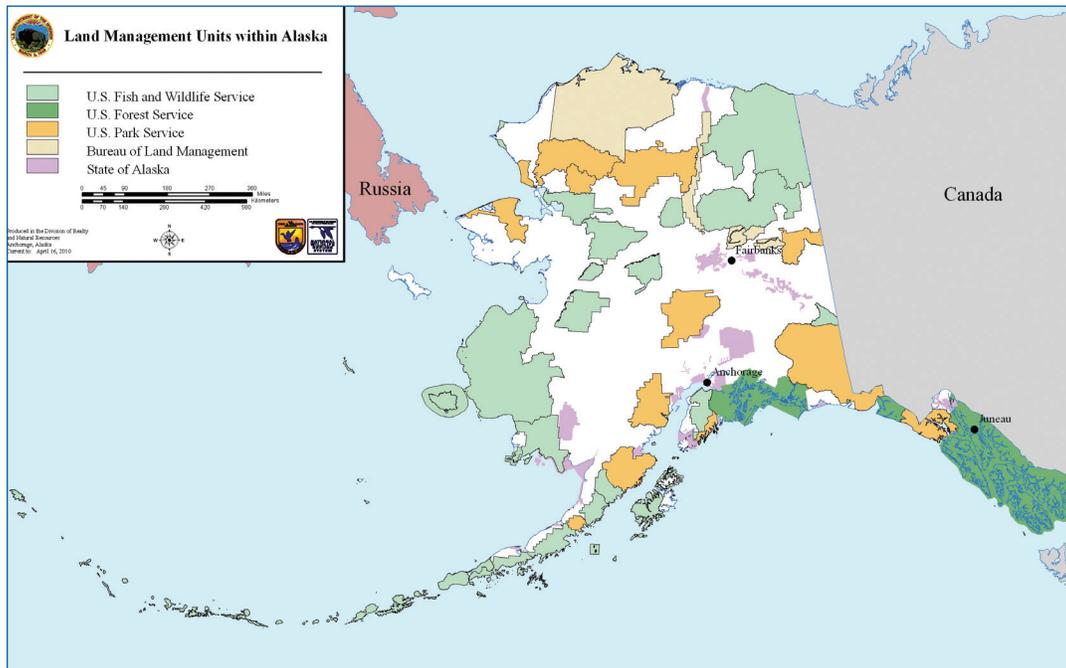


Figure 9 – Conservation lands in Alaska. Although conservation status was not used as a modeling criterion in this project, results can be viewed in light of existing land ownership, use, and protection.

Methods

For the purposes of the Connectivity Project, participants decided on a simple suite of criteria to test the concept. It is important to recognize that these criteria were largely arbitrary and would need serious consideration in future applications. The Marxan model was used to optimize solutions for the presence of biome refugia, two different NDVI criteria, and specific percentages of the landscape. For each biome, modeling was performed within the land area defined by the presence of that potential biome at any modeling time step (2000–2009, 2030–2039, 2060–2069, 2090–2099).

Marxan models are designed to evaluate landscapes to compare how different places meet objectives set by land managers. Two important assumptions in Marxan modeling are 1) not all objectives can necessarily be met simultaneously at the most optimal level; and 2) it is not necessary (and may not even be possible) to find a single mathematically ideal solution. Instead, Marxan searches for “acceptable” solutions—solutions close to the theoretically ideal solution—using a process called simulated annealing. In each step of this process, the algorithm replaces the current solution with a generally preferable “nearby” solution, while allowing some counterintuitive adjustments to avoid stopping the search at a local minimum rather than the global minimum. Simulated annealing is typically used in optimization problems with unmanageably large numbers of objects or pixels or noisy data. Our model was stochastic. The simulated annealing algorithm was run 50 times, and solutions were selected based on the most-frequently selected solutions from those runs.

CRITERION 1: BIOME REFUGIA

To determine where biome function might be most resilient to climate change, we first looked for areas that our models predicted would remain part of the same biome climate envelope over the course of this century. Specifically, we assessed change in the three periods between our sample decades (2030–39, 2060–69, and 2090–99). Since we divided the twenty-first century into three time steps, each pixel on the map had the opportunity to change potential biomes up to three times (Figure 10). A point on the map undergoing two or three changes might change to a different potential biome and then change back, or might shift to several distinct biome climate envelopes in sequence. A pixel experiencing zero changes would remain in the same biome classification at every time step. We considered groups of pixels with no change to be areas most resilient to climate change, at least from the perspective of habitat conditions. We considered these areas of no change as possible refugia for species representative of each biome (Figure 11). In our Marxan model, we optimized the selection of these areas.

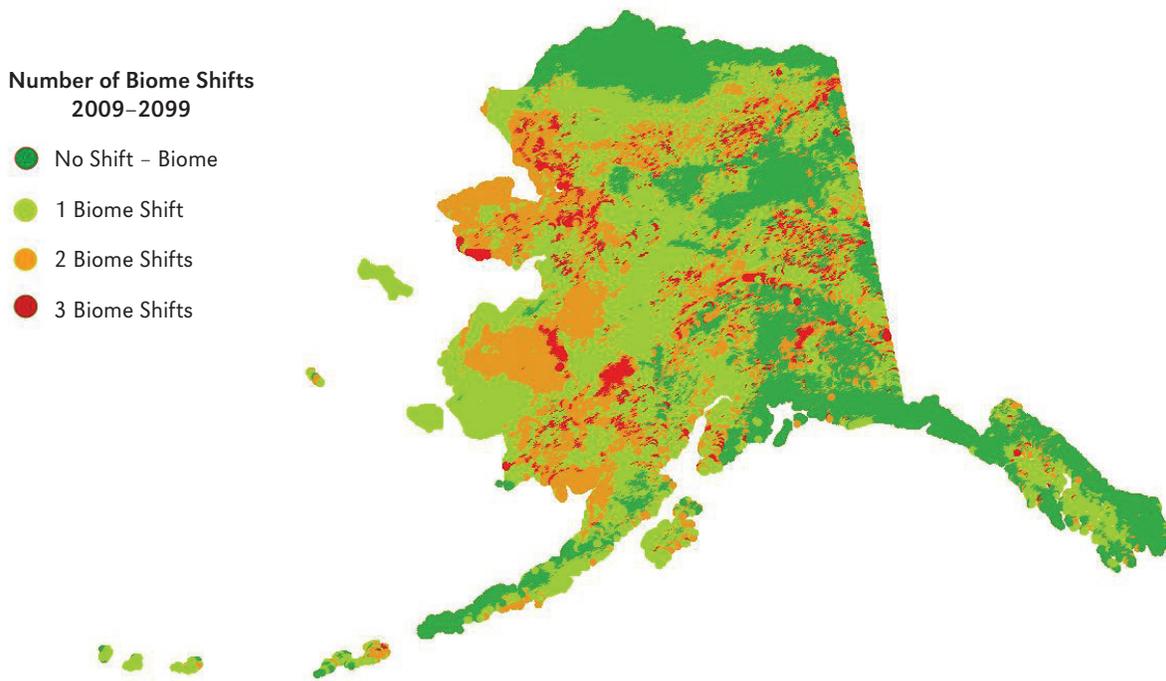


Figure 10 – Number of potential biome changes projected by 2099. Areas showing no change (dark green) are considered refugia for existing species assemblages, while those showing one, two, or three changes (light green, yellow, or red, respectively) are more likely to experience dynamic changes in species populations and challenging management choices.

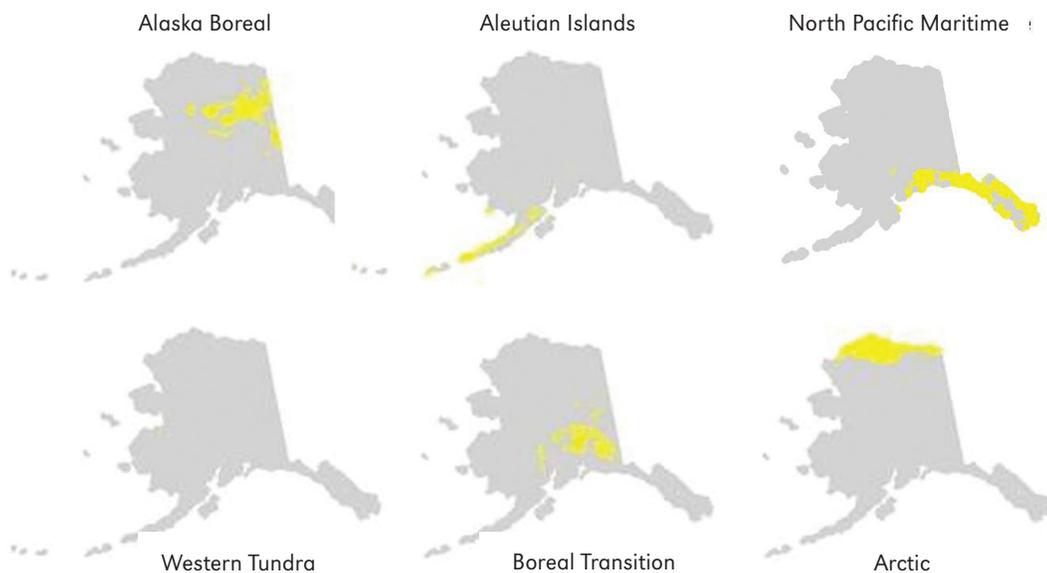


Figure 11 – Biome refugia. Areas shaded in yellow are projected to see no change in potential biome by the end of the twenty-first century. Thus, these regions may be more ecologically resilient to climate change and may serve as refugia for species assemblages from each biome.

**CRITERION 2:
NDVI AS AN INDICATOR OF PRODUCTIVITY AND ENDEMISM**

The Normalized Difference Vegetation Index (NDVI) is a remote sensing indicator used to analyze the relative reflection and absorption of energy in the photosynthetically active radiation spectrum versus the near infrared spectrum. NDVI is directly related to the photosynthetic capacity and hence energy absorption of plant canopies. High NDVI is a well-accepted proxy for biological productivity and is increasingly being explored as a proxy for biological diversity (Verbyla 2008). Low NDVI would be more typical of low productivity habitats such as alpine zones, where we would expect to find at-risk endemic species that have evolved strategies to occupy marginal environments to minimize competition (Spehn and Koerner 2009). As in the case of the Alaska marmot, low NDVI may be associated with endemism in Alaska.

For the purposes of this project, we were interested in areas of both high NDVI and low NDVI. Thus, we used the cumulative averages of historic NDVI levels for each pixel (Figure 12). Marxan optimized the upper and lower deciles of these values. In the future, there may be other opportunities to incorporate NDVI in these types of models. For example, incorporating the initiation of green-up or focusing on the end of the growing season may provide more information for some modeling objectives.

**Alaska 40km Hexagonal Planning Units
Mean Normalized Difference Vegetation Index**

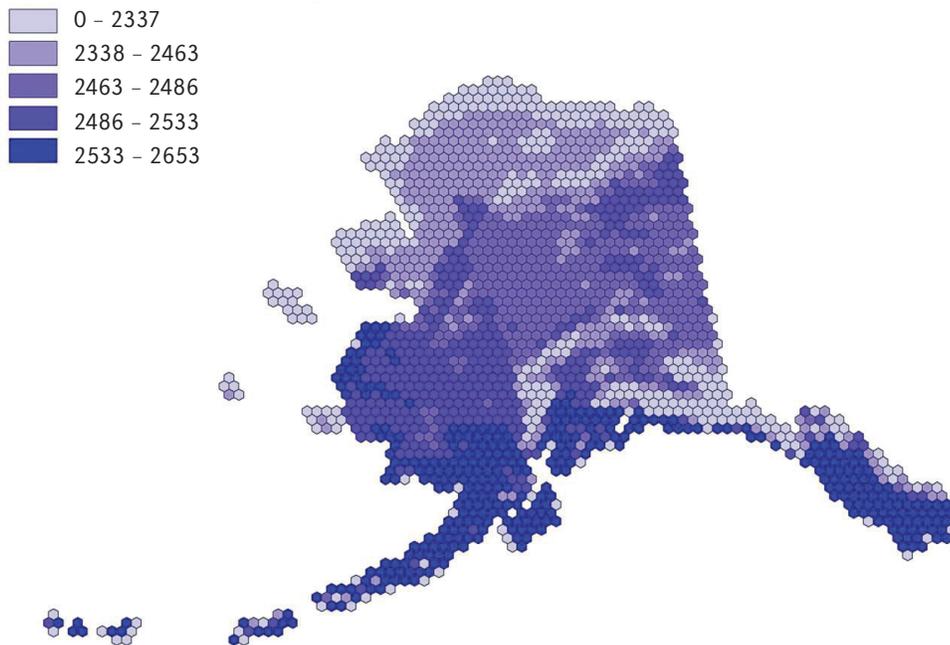


Figure 12 – Historical mean NDVI across the state of Alaska. Areas of highest NDVI (darkest blue) indicate areas of potentially high productivity, while areas of lowest NDVI (lightest blue) may indicate areas of high endemism.

CRITERION 3: PROPORTION OF LAND AREA IN CONSERVATION STATUS

For the modeling results described in this report, we did not optimize each location based on its current conservation status. In preliminary model runs, we experimented with including conservation status as a ranked criterion, with levels ranging from no conservation mandate to designated Federal Wilderness. This avenue could be reopened in future model iterations.

We did consider limitations on land area imposed by variable land status, however. Marxan identified the best areas to select if one was seeking to cover 10% of Alaska or 25% of Alaska with areas that best met the refugia and NDVI criteria within each biome.

MODELING STEPS

Our first modeling step was the conversion of our 5 km gridded data sets into 40 km hexagons in order to make them compatible with Marxan and more manageable in size, and to better represent the smallest units for functional conservation at the landscape level (Figure 13). Again, the selection of this hexagon size was largely arbitrary. Marxan then found potential solutions based on 50 stochastic runs of the annealing algorithm, optimizing for the three criteria described (Figures 14 and 15). In each solution, each hexagon was assigned a quantile rank, with red hexagons being those selected in the highest proportion of runs (highest 1/3), orange being second-ranked (middle 1/3), yellow being less optimal (lowest 1/3), and gray denoting “no solution” (hexagons never selected in any runs).

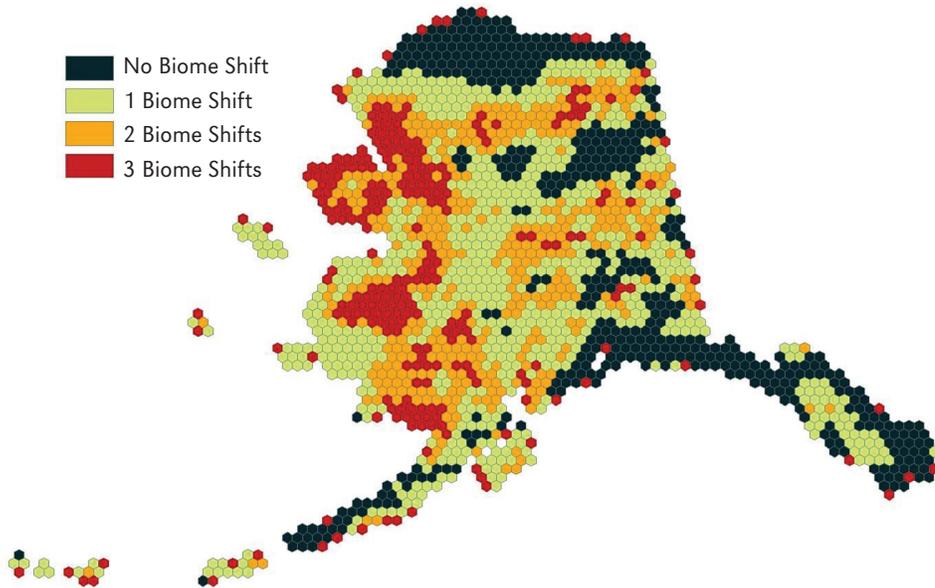


Figure 13 – Biome refugia on a 40 km hexagonal grid. This coarser data set was used for modeling connectivity to make the calculations manageable within Marxan. Land area is classified according to how many changes in potential biome are projected to occur in three future time steps.

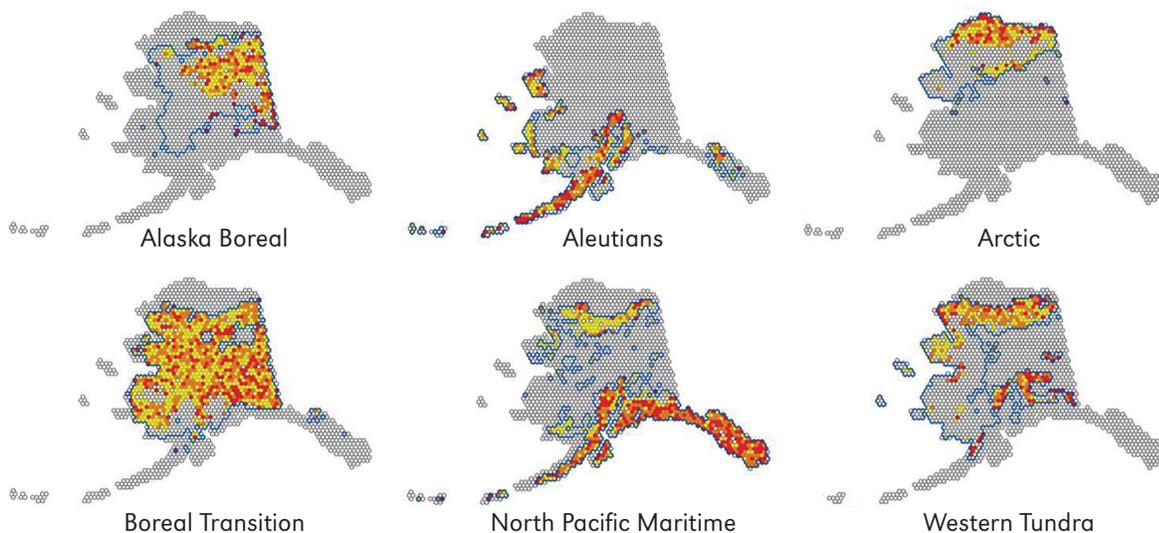


Figure 14 – Marxan solution illustrating ranking by biome assuming 10% of total land area in conservation status. Each hexagon is scored based on NDVI (with both the highest and lowest NDVI deciles being optimal), and number of projected potential biome shifts, with lower numbers preferred over higher. Solutions are constrained to the area in which each potential biome is projected to occur at one or more time steps out to 2100 (blue lines). Red is the best solution, orange is next best, then yellow.

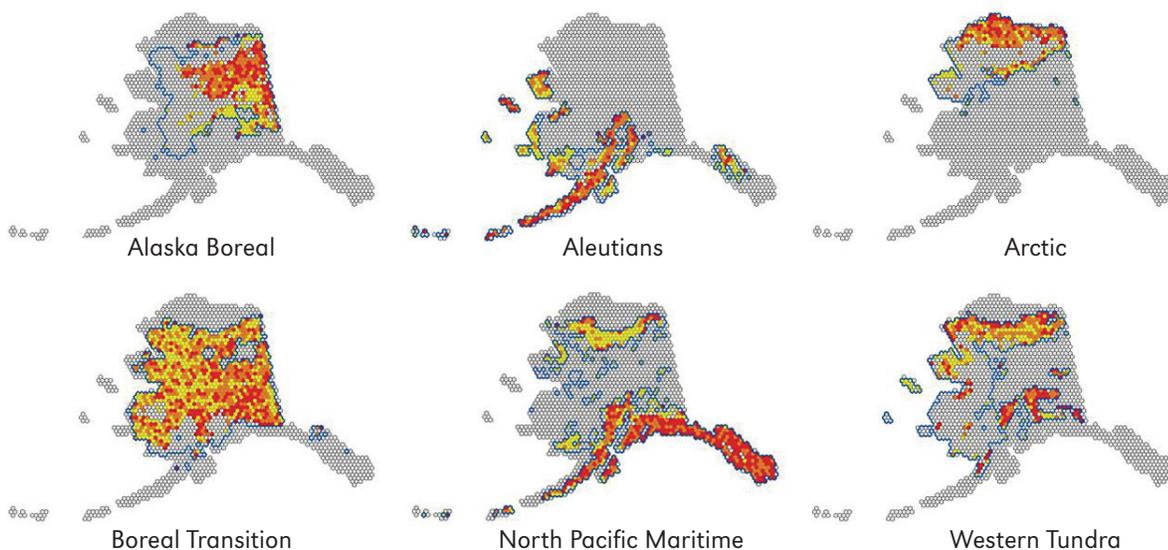


Figure 15 – Marxan solution statewide by biome assuming 25% of total land area in conservation status. Each hexagon is scored based on NDVI (with both the highest and lowest NDVI deciles being optimal), and number of projected potential biome shifts, with lower numbers preferred over higher. Solutions are constrained to the area in which each potential biome is projected to occur at one or more time steps out to 2100 (blue lines). Red is the best solution, orange is next best, then yellow.

Due to the properties of Marxan and the simulated annealing process upon which it is based, overlap between solutions can be expected to be imperfect. For example, 10% land cover solutions for each biome are similar to 25% solutions, but are not a perfect subset of the larger solutions. Moreover, the red pixels for the 10% solution do not add up to exactly 10% of the landscape, since each solution must balance between the competing and sometimes contradictory demands of the variables that are being optimized.

Marxan Modeling Results

In general, we find that the Boreal Transition, Aleutian, and Northern Pacific Maritime regions in the southeast portions of the state are more likely to be resilient to change. Regions within today's Western Tundra, Arctic, and Alaska Boreal biomes are least likely to remain within their original climate envelopes. In the western part of the state, very little land is projected to remain unchanged, leaving little opportunity to connect between refugia and the new areas that may suit the Western Tundra biome. In this region, a more sophisticated process that incorporates changes at intermediate time steps may be warranted to identify important connectivity areas.

While Marxan can be used to identify zones to connect, we found that once each grid cell was ranked, drawing in connections by hand was more effective than additional modeling. We drew connections by hand for each biome using Marxan solutions and conservation status maps as guides and using the intermediate time steps for the biome being modeled to help guide the selection of a connectivity path (Figure 16). If this exercise were being done as part of a true conservation planning exercise, we would bring in additional data layers such as topography and land status to guide connectivity selection. However, in this proof-of-concept approach, we did not include any of these refinements. To the best of our knowledge, this is the first time that linkages have been developed through both space and time. We believe this type of analysis is critical in considering network designs to address rapid climate change.

Discussion of Marxan Results

The biome shift and Marxan results yield some intriguing possibilities for future collaborative work, but our results are obviously based on hypothetical objectives, which need to be refined before use in a statewide adaptive planning exercise. Some of the recommendations identified through this project to improve the modeling process include:

- Use robust projections of potential biome shifts (i.e., based on more of the available temperature and precipitation data and smoothed between the U.S. and Canada prior to establishing the initial climate envelope description for each biome).
- Work with partners to establish landscape-scale objectives (e.g., biodiversity or sustainable harvest of game) that can be represented through spatial layers such as NDVI.

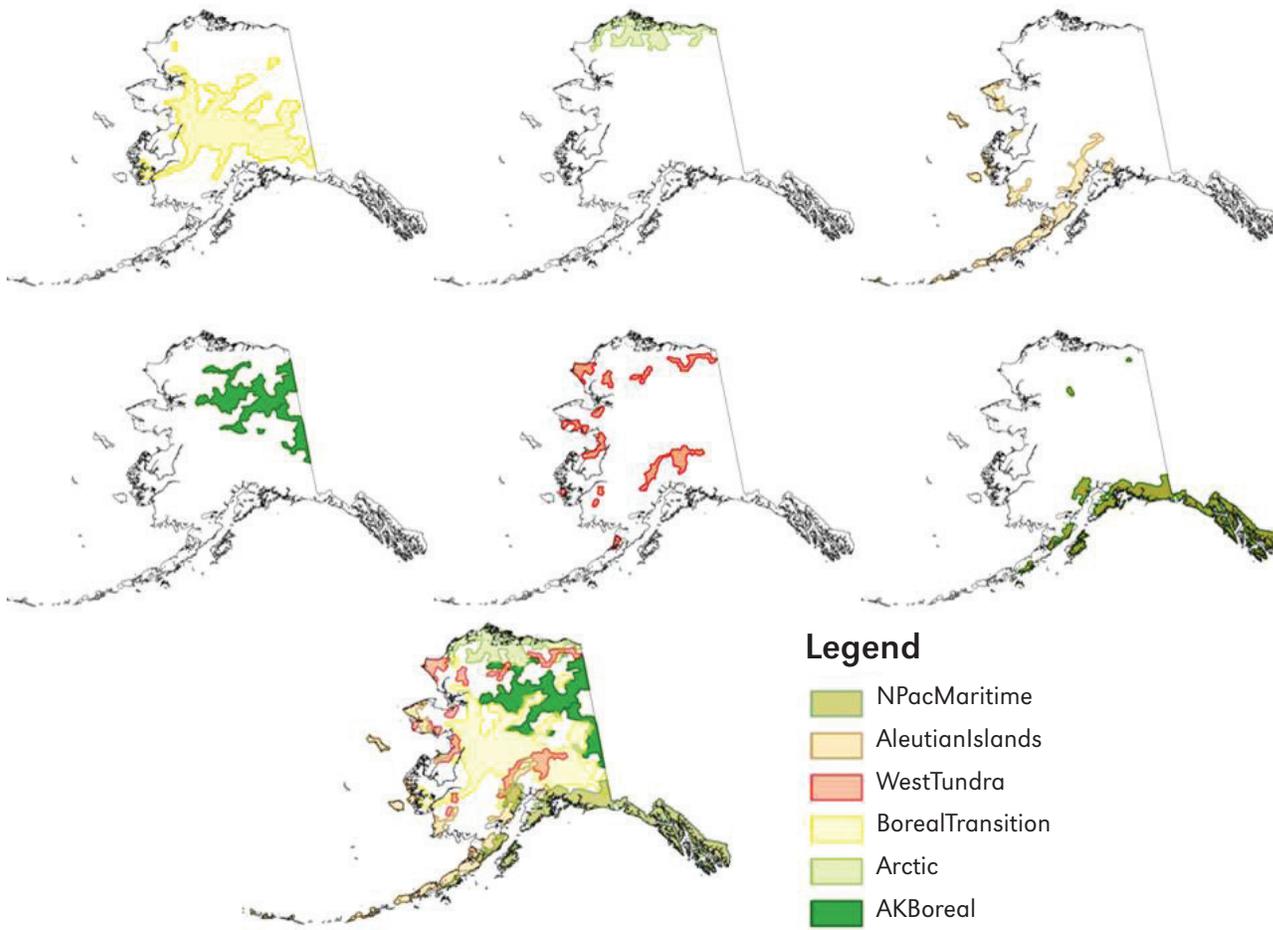


Figure 16 – Potential connections between Marxan solutions for lands within each biome category. These polygons were drawn by connecting the highest ranked (orange and red) hexagons from Fig. 14, which showed where each biome climate envelope was predicted to occur in the future. Note that overlap occurs where the climate envelopes overlapped between multiple biome categories. Drawing these connections by hand proved more expedient than using further modeling techniques, although future refinement is possible.

- Consider how to prioritize the importance of areas where new potential biomes occur on the landscape and how to connect them, if at all, through space and time to their original biome locations.

From a management perspective, the results of this type of modeling can help identify areas to prioritize for monitoring, identify areas of research, and identify areas on the landscape that may be important linkages in time and across the landscape as our climate changes. These important linkage sites, where they fall within conservation lands, should influence land management of the conservation unit. Where important linkage sites fall outside of conservation lands, the model results provide information to state and private land managers for consideration in their management. Recommendations for future research include focusing on boosting model accuracy through field validation, delineation

and monitoring of potential refugia, and exploring opportunities to develop anticipatory adaptation responses in parts of Alaska. For example, we could stratify research natural areas (RNAs) by whether they are refugia or transitory and establish long-term monitoring within each category.

In some areas of Alaska, the potential future biomes indicated by our models are highly disconnected from existing biomes, or suggest extreme range expansion over a short period. For example, projections for the 2090s show Montane Cordillera, a Canadian biome currently occupying most of southern British Columbia and a portion of southwestern Alberta, as the best fit for the future climate of much of Western Alaska. The Boreal Transition biome, which is currently limited to the Alaska Range and southcentral Alaska, is projected to be the best fit for areas as far north as Kotzebue and Arctic Village. In such cases, gradual species shifts are unlikely to occur. Managers may have to choose either to manage for maintenance of biomes less well suited to new climate conditions, or to consider facilitated migration.

Our criteria were selected without serious consideration of the consequences of the choices or their potential achievements. For example, while we had a rationale for incorporating NDVI into the criteria, we could have chosen other approaches than using the top and bottom 10%. We need to consider how to prioritize connection areas for either biomes or species, and whether such an approach would be useful for multiple species. In using this type of modeling for landscape conservation planning, it is important to recognize that many management objectives could be modeled. One of the strengths of using models in landscape planning is the ability to compare the results when different model criteria are used. Marxan is designed to handle a much broader range of criteria than those used in this iteration. At the same time, clear documentation of criteria in scenarios made will be necessary for achieving reproducible results.

Part III **Modeling Changes in Distribution of Indicator Species**

The Connectivity Project originally started with the idea that we could evaluate landscape connectivity characteristics for organisms with different life history traits (i.e., how easily they can migrate). To investigate this concept at a statewide scale, project participants selected four species with very different connectivity issues. Caribou were selected to represent mammal species with few migration constraints; Alaska marmot were selected to represent mammals with limited range and migration capability; trumpeter swans were selected to investigate how statewide landscape connectivity issues would apply to breeding bird populations; and reed canary grass was selected as an invasive plant species that uses our human footprint on the landscape for initial dispersal and may benefit from a warming climate.

In addition, there was interest in understanding how this process could apply to vegetation communities. Since the Connectivity Project was initiated at a time when draft LANDFIRE products were just becoming available, the group decided to use the draft land cover data for the two map zones that were completed earliest. See Technical Addendum III: LANDFIRE Mapping of Units 70 and 71 for more detail on these modeling efforts.

Caribou



Barren-ground caribou (*Rangifer tarandus granti*) are an important case study because of their importance as a subsistence and economic resource in Alaska and because they are a migratory species with different habitat needs during different seasons. Alaska Department of Fish and Game (ADF&G) caribou biologists created range depictions for 33 caribou herds in the state as of 2008 (Figure 17). For most herds, these data include only a combined range area over all seasons, whereas some herds have defined summer and winter ranges. A few of the better-studied herds have more detailed data, including calving grounds. Caribou exhibit wide variation in degree of migratory behavior and other ecological adaptations across North America, and recent taxonomy broadly describes the migration pattern and ecotype of herds as migratory (tundra or mountain) and sedentary (boreal forest or mountain) (Hummel and

Ray 2008:51–52). In Alaska, all herds are considered barren-ground; however, the Chisana herd on the Alaska-Yukon border is officially considered the northern mountain ecotype of woodland caribou in Canada. (Zittlau et al. 2000; L. Adams, pers. comm. 2010). Caribou herds have been defined largely by fidelity to distinct calving areas, although variation in spatial use patterns occurs and defies simple definitions. Herd use of seasonal ranges may vary in size and location as size of the herd changes over time (Davis et al. 1975; R.D. Boertje, pers. comm. April 2010), which complicates inference on habitat selection in response to vegetation changes induced directly (e.g., fire) or indirectly (e.g., climate).

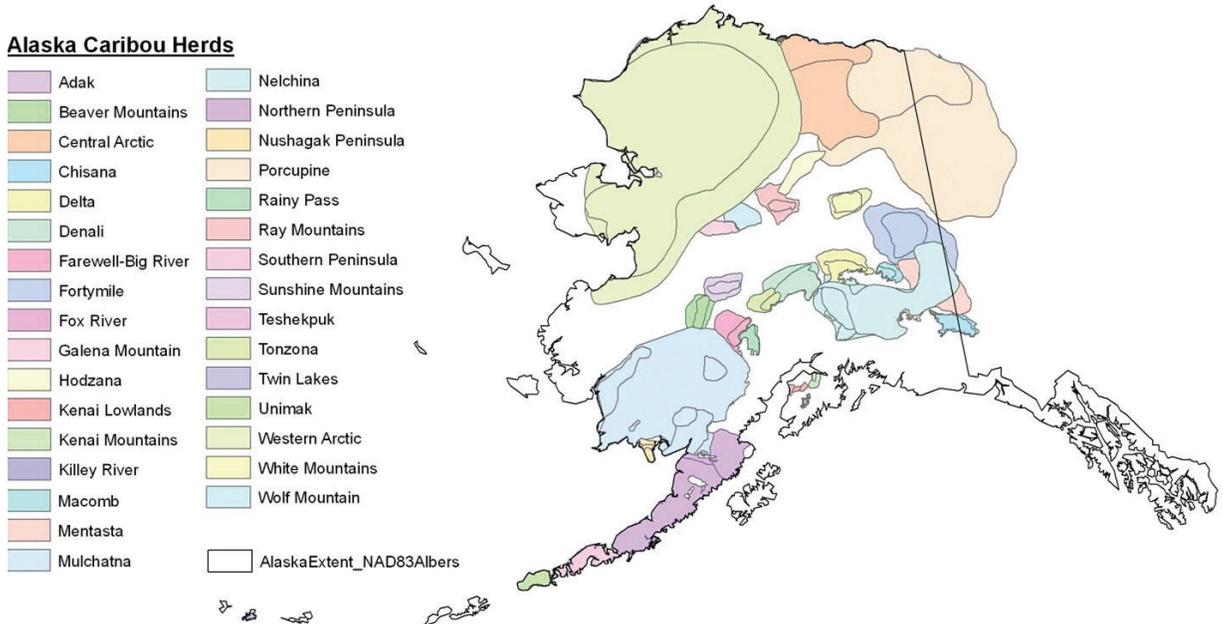


Figure 17 – Alaska caribou herd ranges (2008). Caribou exist in a wide range of habitat types and climates across the state, although herds appear more constrained when delimited by summer and winter ranges. For some herds, additional information is available, such as calving ground locations.

Caribou ranges were assessed in Random Forests™ using temperature and precipitation data for June and December for the decades 2000–2009, 2030–2039, 2060–2069, and 2090–2099. We tried several modeling approaches to capture the adaptable nature of these animals and learned a lot about how early decisions to define “existing conditions” within the model change the model results. At first, we considered southern herds separately from northern herds, since we reasoned that northern herds may have noticeable decreases in their range areas, while southern herds may expand. However, caribou biologists were adamant that caribou are so adaptable that this was an artificial distinction. We also looked at summer and winter ranges because we anticipated that seasonal changes may be more informative. We tried tying these modeling results to the results from Boreal Alfresco climate models, which raised several research questions regarding

the appropriate way to link two climate-based models for the same area. Since only a few herds had specified summer or winter range, this constrained the available data to establish existing climate envelopes. See Technical Addendum V: Caribou Modeling by Herd for further details on this process. In the end, we decided that the most robust approach, given the available data, was to look at total range for all herds combined (Figure 18).

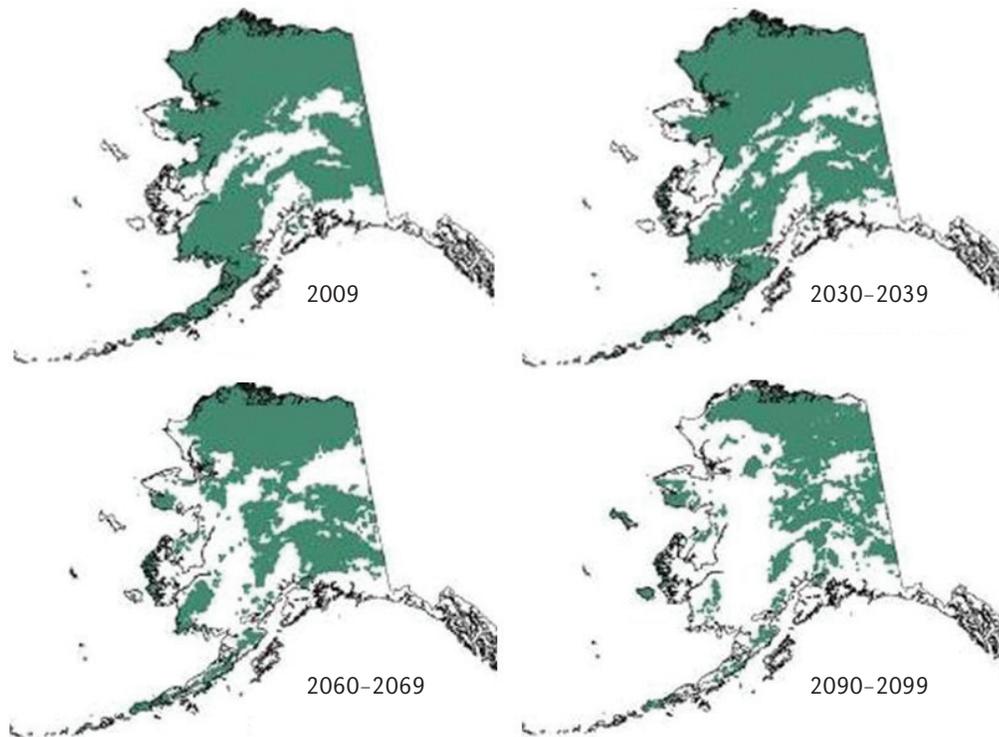


Figure 18 – Projected caribou range for all herds combined. Although climate modeling indicates that ranges may shrink, with a shift in climate-suitable ranges toward the eastern half of the state, this type of climate-envelope modeling for Alaska caribou herds is impractical at a statewide scale because of species plasticity and overlap between herd ranges.

Our model output was the predicted ranges based on climate-derived distribution of biomes that lacked information on specific habitat criteria, such as abundance of forage biomass or the depth and density of snow. We anticipated a substantial change in predicted range distribution in Western Alaska, where future climate envelopes were expected to be poorly matched with existing climate envelopes for herds in that area. For a species as widespread as caribou, it may be best if models are run using climate envelopes for global caribou populations. This broader assessment could show that climate changes in western Alaska are not likely to affect the suitability for caribou in general; however, individual herds may respond differently to changes in climate. The genetic makeup of individual animals within a herd may make them more, or less, adaptable to changes in climate. Recent genetic research on non-migratory herds of mountain caribou in the Yukon Territory concluded that “in the face of increasing anthropogenic pressures and climate

variability, maintaining the ability of caribou herds to expand in numbers and range may be more important than protecting the survival of any individual, isolated sedentary forest-dwelling herd” (Kuhn et al. 2010, p. 1312).

Inferring climate effects on distribution or abundance of barren-ground caribou is complex, because the species often encounters a wide range of habitat during migration and dynamics are influenced by many factors. Sharma et al. (2009) reviewed the influence of biotic and abiotic conditions on the distribution of migratory (barren-ground) caribou, including snow depth, lichen cover, insect avoidance, and predator avoidance. Winter icing events, particularly early in winter, when shallow snow is melted and encases ground forage, can result in mortality of caribou (e.g., Miller and Gunn 2003) or seasonal displacement from affected ranges. These icing events on vegetation are difficult to predict spatially or temporally from broad-scale temperature and precipitation. Icing is an abiotic event that functions independently of caribou density in a “non-equilibrium grazing system” (Miller and Gunn 2003, p. 388).

Classic corridor-type connectivity modeling for Alaska caribou herds is impractical at a statewide scale because of species plasticity and overlap between herd ranges. Species adaptability may allow caribou to utilize habitats in unexpected ways, as witnessed by the transplant of Nelchina caribou to Adak Island, where they achieved large body size on range atypical for Alaska caribou (Valkenburg et al. 2000). Finally, change in caribou abundance and distribution is known to have varied substantially over the last 250 years, based on records of tree scarring by hooves in barren grounds of northern Canada (Payette et al. 2004; Zalatan et al. 2006). These researchers recognized that effects of harvest, predation, fire, and climate can influence herd dynamics over long periods. Because of the complexity of caribou herd dynamics, generalizations about where caribou can and cannot thrive based on climate-driven modeling should be considered hypotheses to be tested for plausible mechanisms with empirical data.

Alaska Marmots



The Alaska marmot (*Marmota broweri*), a relic species from the Beringia Ice Age, has limited adaptability and dispersal ability (Gunderson et al. 2009) and thus makes an excellent case study for connectivity and habitat loss for endemics (native species) in arctic environments. Data for 34 known occurrences of Alaska marmots were provided by the Alaska National Heritage Program, based on various sources including the Gunderson collections (Gunderson et al. 2009). It cannot be presumed that the species is absent from areas for which no data exist (Figure 19). We hypothesized that shrinking alpine zones and loss of connectivity between remaining alpine zones would limit the potential habitat for this species. For a detailed explanation of our modeling methods, see Technical Addendum VI.

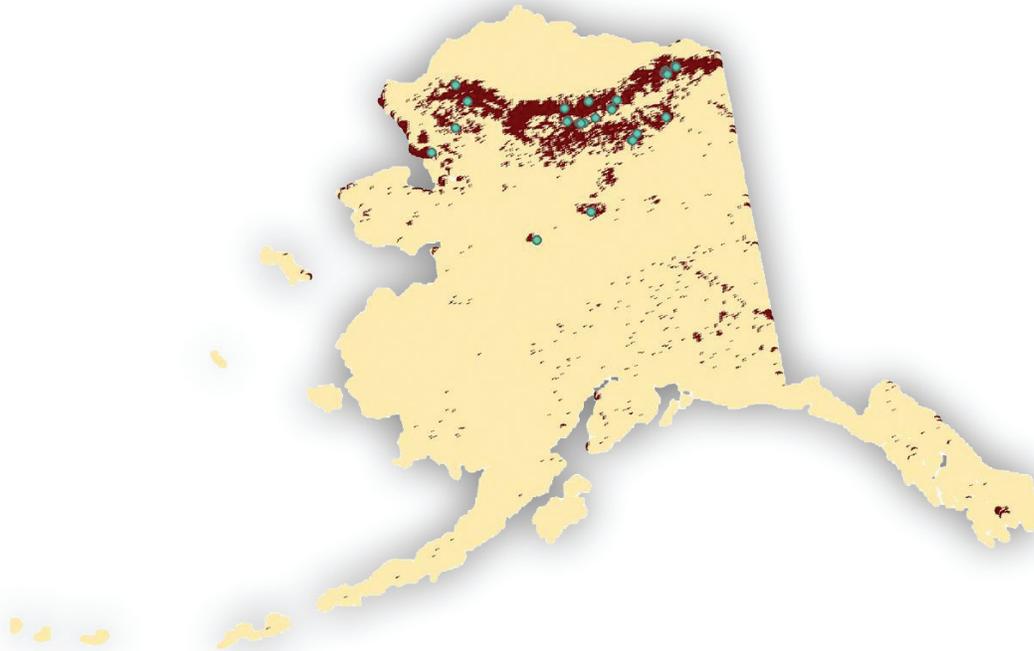


Figure 19 – Known Alaska marmot distribution and modeled current distribution.
 Since no absence data exist, it cannot be assumed that marmots do not also inhabit similar habitat in which no confirmed presence data are available.

As with models described in previous sections, we used SNAP climate data for June and December mean temperature and precipitation for 2000–2009 to develop a climate envelope and current potential distribution based on known occurrence sites. However, we also added terrain roughness as a covariate. Rockiness, steepness, and associated biophysical features are of great importance to marmot habitat, since Alaska marmots use rock piles for cover. Terrain roughness was estimated based on a localized digital elevation map (DEM) depicting rate of slope/aspect change. Terrain roughness is likely to be minimally affected by climate change; therefore, the same values could be used for each 30-year time step.

Confirmed sightings of Alaska marmots have occurred in alpine areas in the Arctic and sub-arctic regions of the state. Initially we used presence/absence of the Alpine biome as a final covariate in our analysis, but the existing alpine area did not correlate well with known marmot occurrence, and predicting alpine zones proved difficult given the lack of availability of pertinent data sets (see Technical Addendum II: Identifying the Alpine Biome). Terrain roughness proved to be more accurately and reliably measured, and thus more likely to be a useful predictor.

Using the covariates mentioned above, results from Random Forests™ modeling showed shrinking range size for the Alaska marmot (Figure 20). Statewide, total range area shrank by 27% by 2039, 81% by 2069, and 87% by 2099, as compared with present estimated range size. In addition, previously contiguous habitat areas became disconnected.

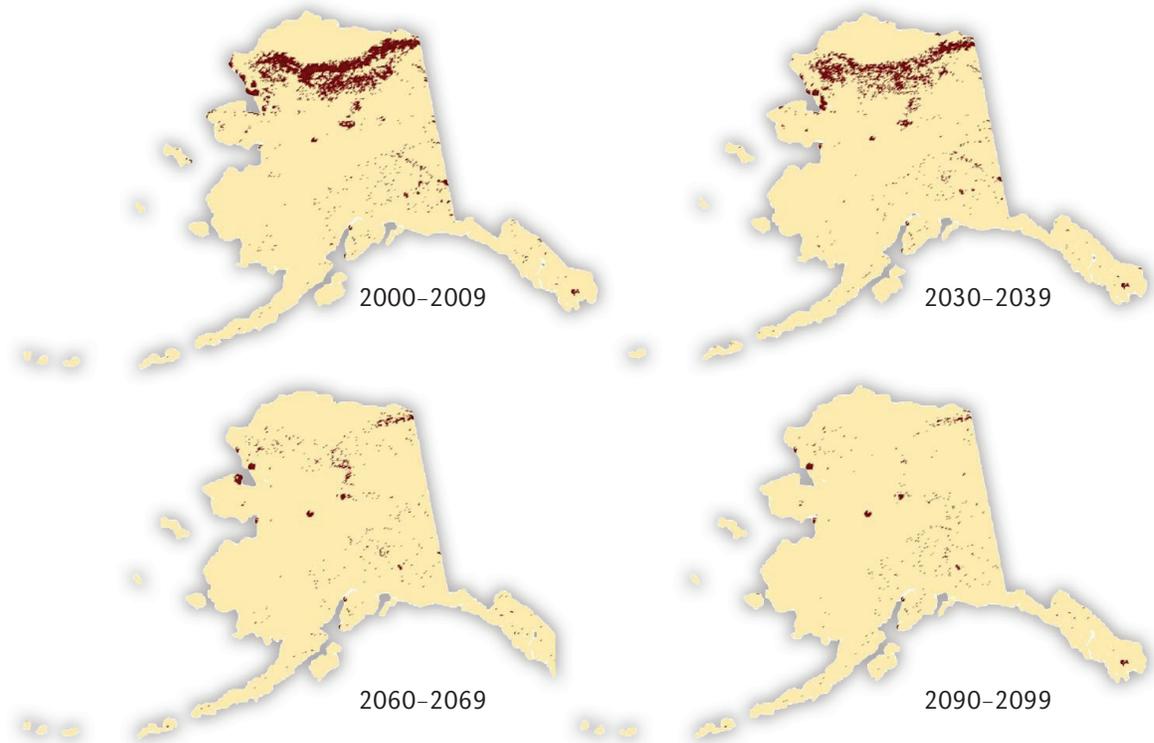


Figure 20 – Projected Alaska marmot distribution. Marmot range is expected to diminish sharply as climate warms and alpine habitat shrinks.

Given the likelihood of limited dispersal ability for this species, the increasing fragmentation of potential distribution areas may present as much of a problem as their shrinking area. Further analysis would be needed to ascertain whether gene flow would become impeded under the projected conditions.

Although the predicted distribution changes of climate-suitable habitat for Alaska marmots is alarming, these results should be considered with caution. There were only 23 georeferenced locations for establishing training data out of 34 sighting records. The Connectivity Project participants are concerned about the validity of using so few point locations to establish a climate envelope. It would be helpful to have researchers establish guidelines on how to scale climate data appropriately. Nevertheless, using this approach to guide future efforts to locate Alaska marmots and expand the available data on this little-understood species would be very informative.

Trumpeter Swans



The trumpeter swan (*Cygnus buccinator*) was selected as a species of interest because, like many other birds species in the state, it is migratory. As such, statewide connectivity of habitat may not be an issue for them. However, quantity and quality of habitat are pertinent to the survival of this species. Swans are limited, in part, by summer season length to fledge their young. We hypothesized that longer summer seasons expected with climate change could potentially expand their overall range. Furthermore, trumpeter swans were an excellent species to model because good-quality data exist for their range and distribution, including survey data for adults, young, and brood size. For a detailed explanation of our data and modeling methods, see Technical Addendum VII.

Using the same methodology and climate data described for modeling biomes, we modeled potential shifts in swan climate-linked habitat, using SNAP temperature and precipitation data for summer and winter for the current decade and three future decades (2000–2009, 2030–2039, 2060–2069, and 2090–2099). Trumpeter swans in Alaska require 138 ice-free days to fledge their young successfully (Mitchell 1994). Thus, we created an overlay of areas predicted to experience greater than or equal to 138 days between the time when the running mean temperature crosses the 0°C point in the spring, and when it crosses it again in the fall. This information was derived from the SNAP climate data. Although water bodies would not be expected to be ice-free as soon as mean temperatures are above freezing, the error introduced by this lag time should effectively be canceled by a similar lag time in the fall.

We also overlaid lands that were predicted to be in non-forested biomes as of 2099 as a proxy for incorporating competitive exclusion between trumpeter and tundra swans (*Cygnus columbianus*). Non-forested biomes included Arctic, Western Tundra, and Aleutian Islands. Trumpeter swans generally occupy forested lakes, while tundra swans are associated more with non-forested lakes. This data layer was likely to be inexact, since, as noted, there is expected to be a significant time lag between potential biome shifts (based on climate suitability) and actual biome shifts (based on climate and vegetation occurrence). Hydrology was not included in our model, because wetlands and other water bodies are ubiquitous across the state and there was no available predictive model to demonstrate changes in water bodies through the century. We modeled occurrence rather than brood size because brood size turned out to be a very weak predictor, perhaps affected more by mating pair experience and age than by climate-driven habitat quality.

Model results showed distribution expanding west and north (Figure 21), but did not predict movement into the Arctic. It should be noted that this shift might be happening already. Since biologists cannot easily distinguish tundra versus trumpeter swans from the air, mixing is probably occurring already at the interface between habitats along the northern and western parts of the range. Further exploration of the ability to model distributions of tundra swan will help to clarify the potential distributions for both species.

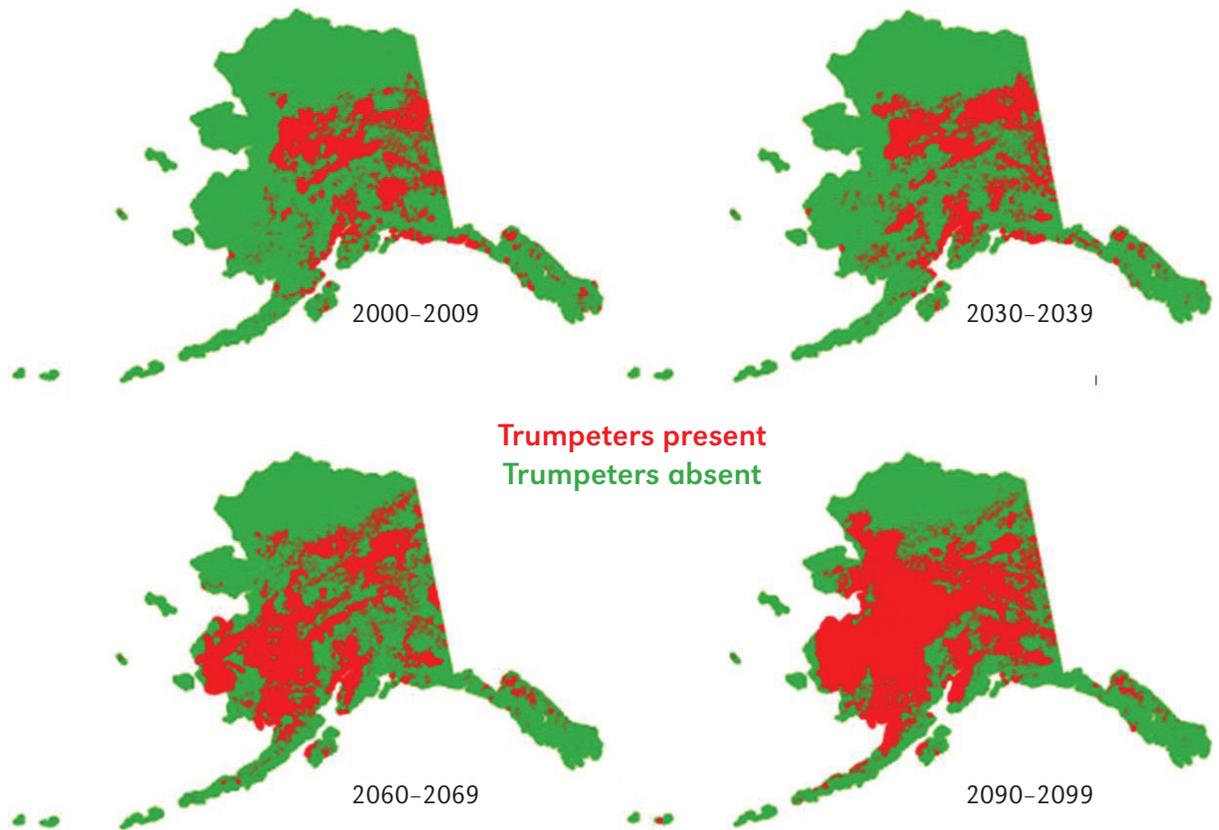


Figure 21 – Potential expansion of trumpeter swan habitat. These predictions are based on 138-day ice-free season, summer and winter climate envelopes, as predicted by SNAP climate projections, and a competitive filter of non-forested biomes to represent tundra swans (not included in this figure). Trumpeter swans are predicted to shift their range northward and westward over the course of this century.

Reed Canary Grass



Reed canary grass (*Phalaris arundinacea*) was selected as a case study because it represents an aggressive invasive species. It is already established on the Kenai Peninsula and elsewhere, and is projected to spread along road and trail systems, and along river systems statewide. Seeds and vegetative fragments float, and seeds, which adhere readily to moist skin or fur, can be transported in clothing, equipment, and vehicles (Wisconsin 2009). Because it clogs waterways, it can have a profound effect on riparian ecosystems (Zedler and Kercher 1994).

Raw data on the occurrence of reed canary grass are available from several sources; however, it should be noted that the species is likely to be widely under-sampled. Data are based on relatively coarse georeferencing, which tends to be located along road/trail systems. We relied on the most comprehensive data set available, from the Alaska Exotic Plant Information Clearinghouse (AKEPIC Database 2005), with approximately 5,000 records through the 2008 field season. For a detailed explanation of our modeling methods, see Technical Addendum VIII.

Dispersal of reed canary grass is clearly through roads and streams, although some isolated road systems are not yet impacted. Therefore, we modeled the potential spread of the species using Department of Transportation (DOT) maps for existing all-season roads (AKDOT 2008). We were unable to model potential secondary expansion through the river systems downstream of introduction sites along roads and trails. Modeling is possible, however, using new hydrological data processing tools within ArcGIS, and should be incorporated into future models. We also explored the possibility of spread through seasonal roads and future roads; see Technical Addendum VIII for details.

As with the other models described in preceding sections, we mapped the known occurrences of the species and linked these sites with SNAP climate data for June and December for 2000–2009. Using this training data, we extrapolated the potential habitat for the species for three future time steps (2030–2039, 2060–2069, and 2090–2099). However, in this model we also used proximity to roads as a covariate. Furthermore, the modeled climatic niche for reed canary grass is based on extant distributions of populations that are rapidly expanding, making the modeling a conservative one.

Our results (Figure 22) show potential spread in the Seward Peninsula by the end of the century. The predicted spread north should raise concerns with managers that this species can present a threat in other high latitude regions of the state. These predictions are very conservative since they do not account for spread via water. In addition, our models do not take into account the potential spread by airplanes (terrestrial and floatplanes).

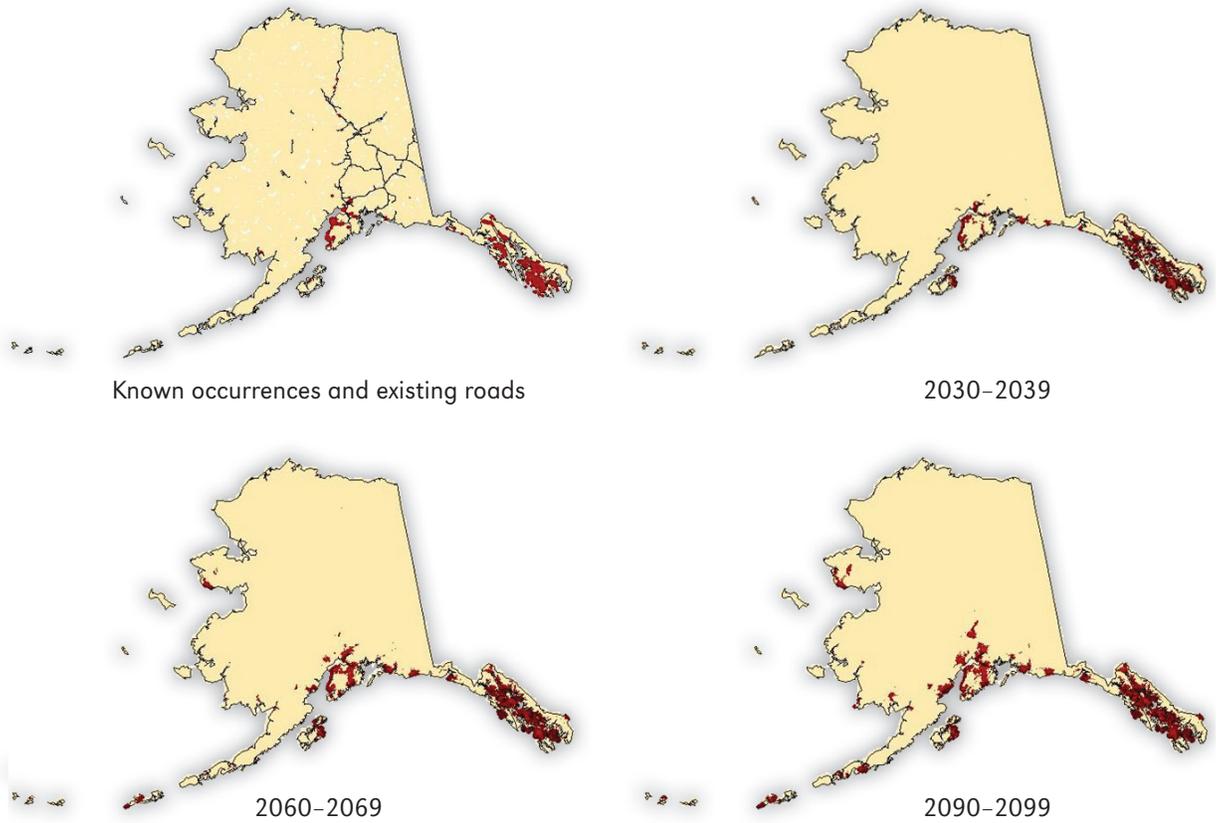


Figure 22 – Potential spread of reed canary grass, using climate and all-season roads as predictors. Inclusion of waterways, proposed roads, and trails would be likely to broaden the modeled range of this invasive species. See Technical Addendum VIII.

Part IV **Implications of Modeling for Conservation, Research, and Management**

The form of predictive modeling that we have developed here has great potential for landscape-level conservation planning. As biological validation occurs with field studies, it may become useful in guiding the direction of on-the-ground management actions. In the past, management decisions have generally been directed toward maintaining or restoring species abundance and/or diversity, based on some approximation of “historic conditions.” Adaptation may now mean managing toward less-certain future conditions, rather than aiming for historical or current conditions (Choi et al. 2007; Harris et al. 2006). The Intergovernmental Panel on Climate Change recognizes that adaptation strategies can be anticipatory or reactive. Anticipatory adaptation works *with* climate change trajectories; reactive adaptation works *against* climate change, toward historic conditions. The former approach manages the system toward a new climate change-induced equilibrium; the latter abates the impact by trying to maintain the current condition despite climate change (Johnson et al. 2008).

The modeling results in this study, albeit preliminary, advance the dialogue that we need to have within our larger conservation community. We can begin assessing the relative trade-offs of doing nothing to address climate change or doing something, and whether that something should be reactive or anticipatory in nature. Our modeling suggests that over the course of this century a dramatic 63% of Alaska will shift to climate conditions associated with a biome other than the current one. Extant distributions of caribou, Alaska marmots, reed canary grass, and trumpeter swans may be very different within a few decades. The Alaska marmot, an endemic species and a *Beringia* relict, may be on a trajectory for extinction within the state if habitat requirements are not better described through informed research on the animal’s life history characteristics, particularly on timing of spring and den emergence. Conversely, reed canary grass, an invasive plant that is currently constrained in distribution to southeast and southcentral Alaska, will likely colonize much of the state as it is dispersed along existing and future roads. In the near future, we need better information on caribou population distributions and their ties to habitat, to anticipate how caribou may respond to changing climate patterns. These future potential patterns should be considered, while also considering management

efforts (e.g., fire suppression to protect lichens associated with mature black spruce, recreational harvest reduction) that reduce non-climate stressors in areas where caribou are declining or expected to decline based on this type of modeling. Our modeling suggests trumpeter swan populations will likely do well under future climate scenarios, but perhaps at the expense of tundra swan populations that may decline because of competitive exclusion, a mechanistic response that is difficult to model with our approach.

The identification of biome refugia perhaps offers the most significant management opportunity in Alaska, where historic ecosystems are mostly intact, and refugia can act as population sources for colonization of novel areas. Two-thirds of predicted refugia over the next century are on federal land designated for some level of conservation; however, only 18% of refugia spatially coincide with congressionally designated wilderness. Wilderness designation or expansion of the federal conservation estate requires an Act of Congress, neither of which has occurred since the passage of the Alaska National Interest Lands Conservation Act (ANILCA) in 1980. Fortunately, there are other tools and approaches to

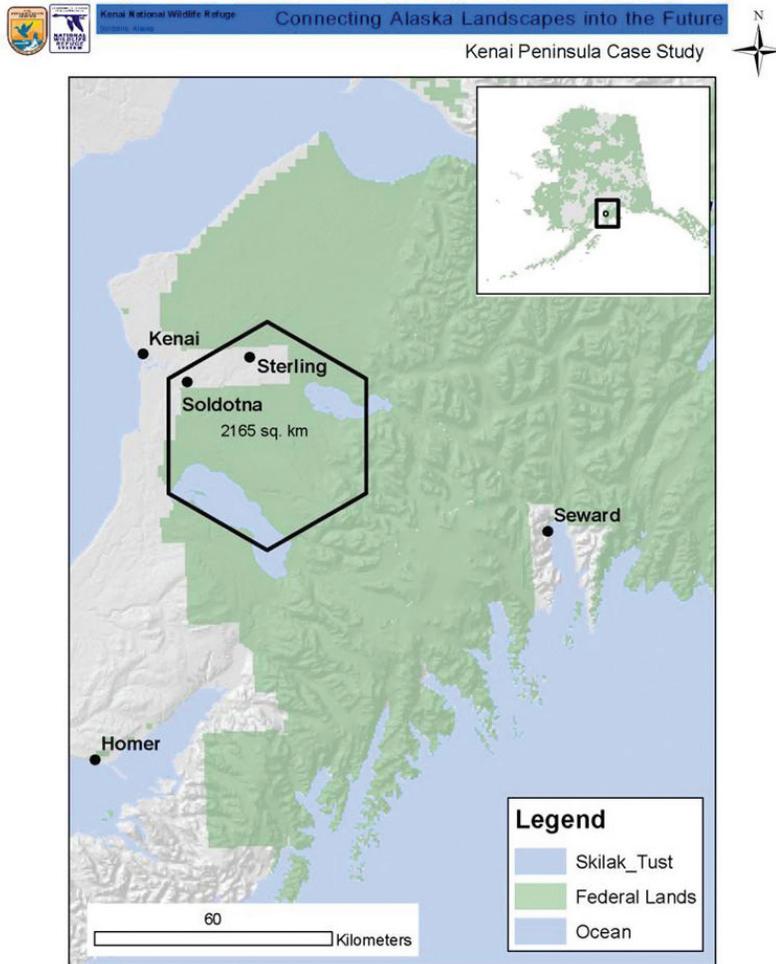


Figure 23 – Case study area, Kenai Peninsula.

strategic land protection including working with Alaska Native corporations and villages interested in identifying and designating refugia as special places to sustain traditional ways of life, as well as a myriad of other approaches. In addition, there may be opportunities to protect landscape-level migration corridors through multi-partnered conservation agreements. In fact, this project was originally funded because of interest in potential partnering with the Yellowstone to Yukon Conservation Initiative (Y2Y). This partnership aims to protect a contiguous mountain corridor, from Yellowstone to the Yukon-Alaska border. Little imagination is needed to picture a partnership that spans Yellowstone to the Yukon Delta or Beaufort Sea.

There may be opportunities to manage habitats to sustain or create dispersal corridors between biome refugia and sites of future biome establishment, or to protect habitats or species from anthropogenic stressors to give them time and space to adapt to a changing climate and environment. In that regard, this type of modeling can re-direct our attention to areas that may be at greatest risk. For example, results from our project imply that the Western Tundra may be our rarest and least-protected biome over the next century.

Supporting Evidence for our Models from the Field: Kenai Peninsula Case Study

The Kenai Peninsula, particularly west of the Kenai Mountains, is forecasted to be highly impacted by climate change over the next century. We examined the predictions from the statewide Random Forests™ model for a 50 km wide hexagon (2165 km²; Figure 23), slightly larger than the hexagon used in our Marxan models. This hexagon was deliberately placed in an area of the peninsula with a relatively diverse landscape: various land ownerships, wide elevational change, and a range of aquatic and terrestrial habitats. In this section, we summarize predicted changes for biomes, reed canary grass, trumpeter swans, and caribou, and describe published and anecdotal evidence that supports (or does not support) these forecasted effects at the local scale.

Kenai's climate: The Kenai Peninsula has a subarctic climate. Temperatures rarely rise to more than 80°F (26°C) in the summer or drop to less than 0°F (-18°C) in the winter. The average annual temperature at the Kenai airport is 33.9°F (1°C). The frost-free growing season varies from 71 to 129 days depending on the location. The Kenai Mountains create a strong rain-shadow on the western Kenai lowlands. Sterling and Kenai, on the western side of the peninsula, receive 17 inches (43 cm) and 19 inches (48 cm), respectively, of precipitation per year. In contrast, Seward and Whittier, on the eastern side of the peninsula, receive 68 inches (173 cm) and 198 inches (503 cm), respectively, of precipitation per year. Annual temperatures on the Kenai Peninsula have warmed several degrees following the warming of North Pacific sea-surface temperatures in 1977. Much of this annual increase is due to warmer winters, with December and January having warmed by 9° and 7°F (13°–14°C), respectively. Summers began to warm most noticeably with the drought of 1968–69, with a resultant increased rate of evapotranspiration. Similarly, the annual water balance declined from 5.8 inches (14.7 cm) to 3.0 inches (7.6 cm) per year after 1968 (Berg et al. 2009).

Biome: The statewide modeling suggests that the potential biome will shift dramatically, from 88% Boreal Transition in 2009 to 84% Aleutian Islands in 2099. A portion of the area will remain within the North Pacific Maritime biome, increasing from 12% to 16% of the landscape from 2009 to 2099. **From the field:** Empirical data indicate that flora within the focal area is representative of the Boreal Transition biome. A supervised classification of Landsat imagery, based on ~4,400 field plots (L. O'Brien, KENWR, Soldotna, Alaska, pers. comm. 2004) indicates that black spruce, mixed hardwood-spruce, and white/Lutz spruce comprise 60% of the landscape (Figure 24). Recent research shows that, indeed, the warming and drying climate in the past 50 years is already impacting processes that affect vegetation composition and distribution including changed fire regimes (Berg and Anderson 2006; DeVolder 1999; Morton et al. 2006), increased spruce bark beetle outbreaks (Berg et al. 2006), accelerated glacial ablation (Adageirsdottir et al. 1998; Rice 1987), drying wetlands (Klein et al. 2005), tree line invasion into alpine tundra (Dial et al. 2007), and shrub encroachment into historical peatlands (Berg et al. 2009). While we know the landscape is changing rapidly in response to climate, it is not as apparent that it may be moving toward a shrub-dominated system typical of the Aleutian Islands biome. In the southern part of the peninsula, mostly outside the focal area, much of the white and Lutz spruce forests have given way to a savannah dominated by *Calamagrostis canadensis* in the aftermath of a 15-year spruce bark beetle outbreak. Some of this conversion is due to salvage operations on private, state, and native corporation lands, and the parcelization and development of those lands; but the phenomenon is too widespread to be attributed only to these human actions.

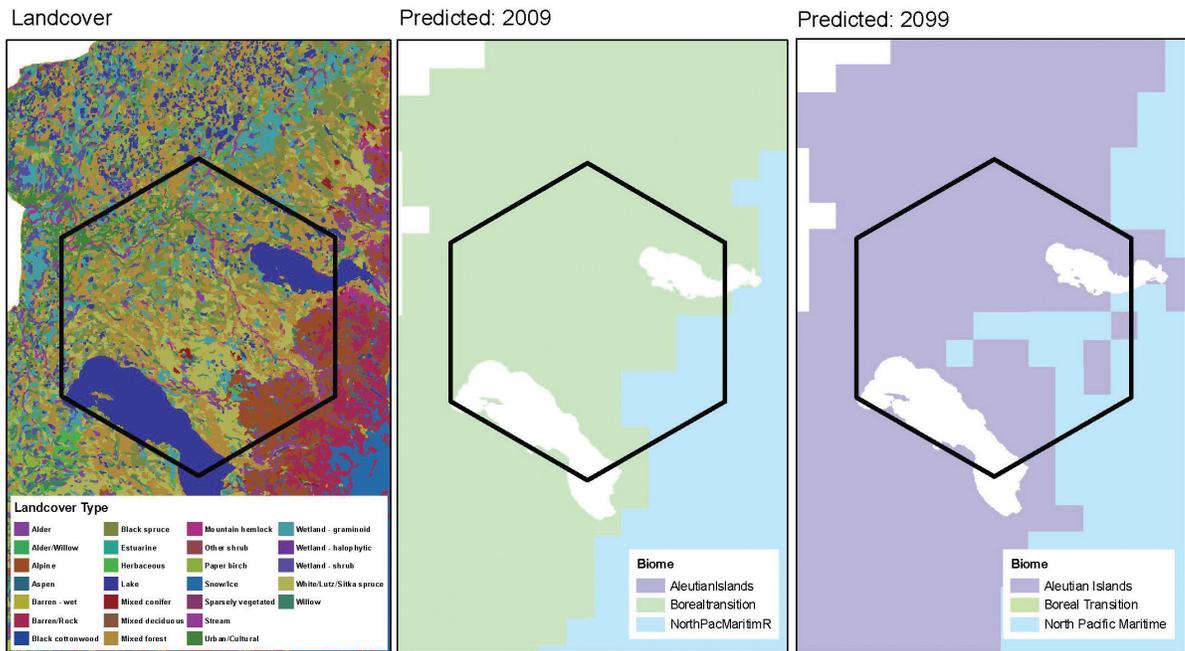


Figure 24 – Landcover, existing biome, and predicted biome. The study area is predicted to undergo a marked shift from climate characteristics of the Boreal Transition biome to climate characteristics of the Aleutian Islands biome.

Reed canary grass: Reed canary grass is a relatively recent introduction to the Kenai Peninsula, but has been rapidly spreading along the road system and streams. The statewide modeling indicates that the likelihood of occurrence increases in the focal area from 0.22 (min=0.3 max=0.86, sd=0.22) in 2009 to 1.0 (min=1, max =1, sd=0) by 2099. **From the field:** Empirical data suggest that modeling of the current distribution approximates what we see on the ground. From 2005-09, there were 786 records of reed canary grass on the Kenai Peninsula, of which 64 occurred within the focal area. The modeling of future distribution suggests that reed canary grass will continue to spread over the entire focal area (Figure 25). At this time, the only constraint that we can envision is the ability of the native *Calamagrostis canadensis* to outcompete reed canary grass in upland habitats.

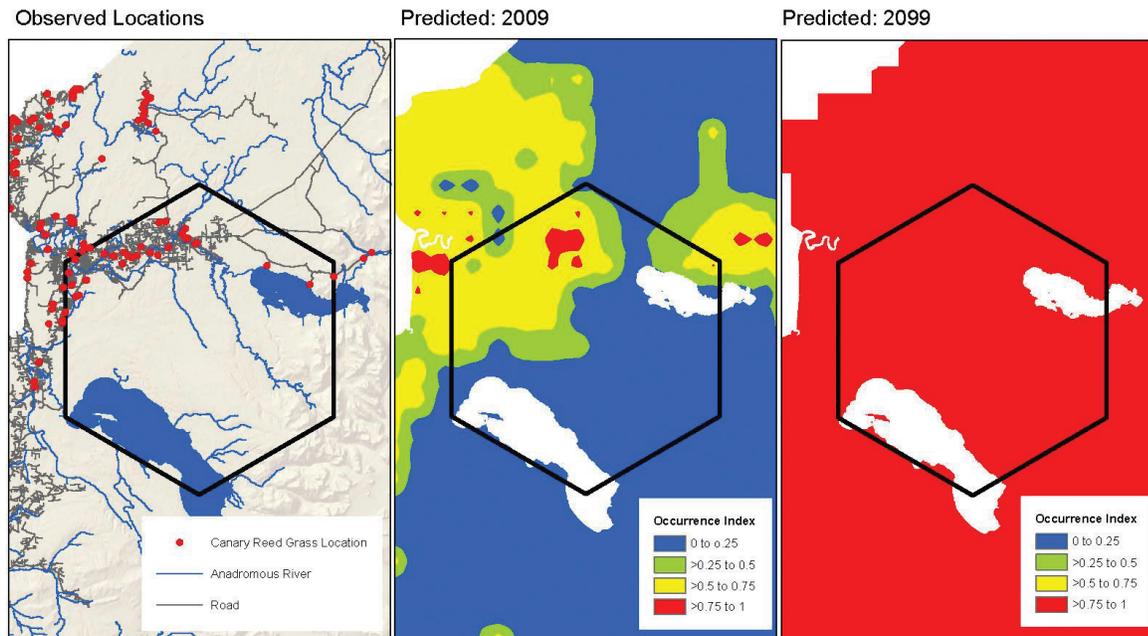


Figure 25 – Modeled spread of reed canary grass.

Trumpeter swans: The Kenai Peninsula is a major breeding and staging area for trumpeter swans, particularly in the Kenai lowlands north of the focal area. The statewide modeling indicates that the likelihood of occurrence increases in the focal area from 0.39 (min=0.07, max=0.82, sd=0.17) to 0.64 (min=0.1, max=0.79, sd=0.14) by 2009 (Figure 26). **From the field:** Indeed, aerial surveys conducted since 1957 indicate that trumpeter swans have increased from 20 to over 50 breeding pairs on the Kenai National Wildlife Refuge. Within the focal area, trumpeter swans were recorded 78 times from 2004-08: 41 pairs, 23 broods, 7 flocks, and 7 single adults. Swan productivity may continue to increase based on projections of increasing frost-free days, but available habitat may be nearing carrying capacity. Additionally, the drying of closed-basin lakes on the peninsula will only decrease aquatic habitat. Increasing human disturbance from the development of private lands within the focal area will further contribute to a reduction in available habitat.

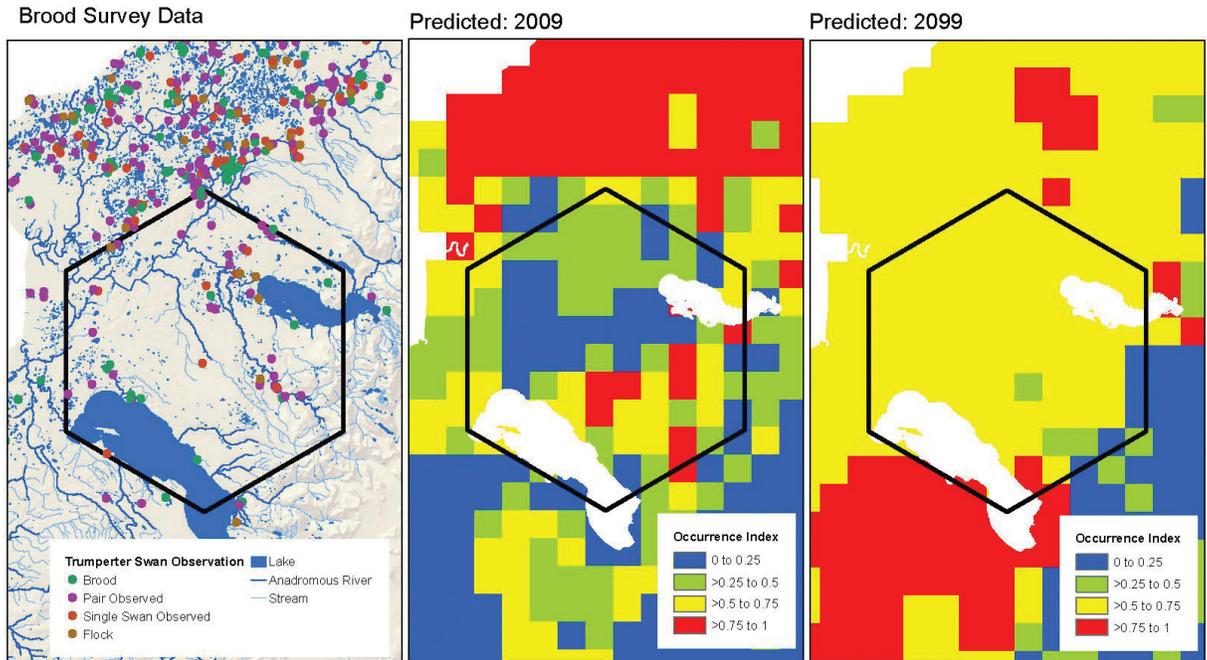


Figure 26 – Increase in likelihood of occurrence of trumpeter swans.

Caribou: Caribou were extirpated from the Kenai Peninsula circa 1917, but were subsequently reintroduced by the USFWS and ADF&G during the 1960s through 1980s. About 1,000 caribou are now established in four herds on the peninsula. The statewide modeling indicates that the likelihood of caribou occurring in the focal area during the summer will not change significantly over the remainder of this century, ranging from 0.21 (min=0.01, max= 0.71, sd=0.20) in 2009 to 0.21 (min = 0.11, max = 0.41, sd=0.11) in 2099 (Figure 27). **From the field:** Shown are 1,889 GPS locations of 4 individuals from the Killey River herd (May–August 2002), of which 833 occurred in the focal area; and 313 locations of 2 individuals from the Kenai lowlands herd (May–August 2001), of which 18 occurred in the focal area. The long-term viability of the Kenai Lowland herd is questionable and will likely be driven by local-scale issues despite a neutral climate prediction, including harassment and mortality due to domestic dogs, habitat loss on the calving grounds due to development, and severing of its migration route by an increasing wildland-urban interface and highway traffic.

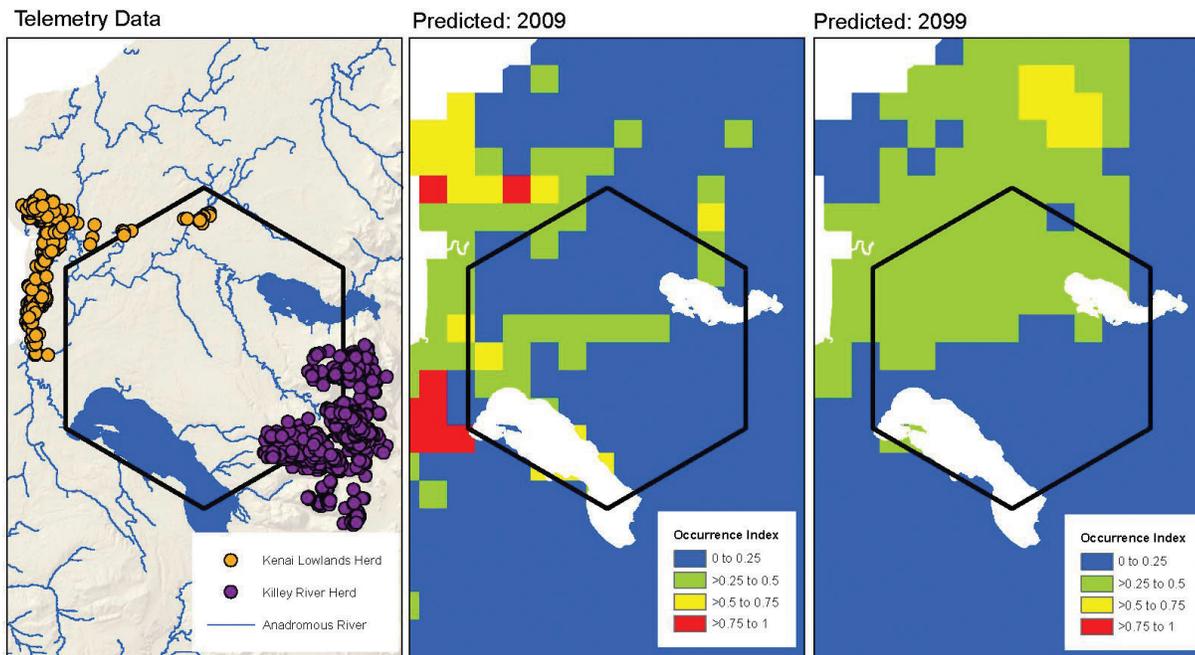


Figure 27 – Little change is seen in potential caribou distribution.

Conclusion: Within the focal pixel, we see reasonable convergence of empirical data in 2009 with modeled projections in 2009. In some ways, this is not surprising given that data from the Kenai Peninsula were captured in the statewide modeling effort. However, this exercise does provide support that, given the similarities between empirical data and model output in 2009, the forecasted future in 2009 is a reasonable scenario.

Implications of Results for Conservation, Research, and Management

These models provide a crucial overview of general patterns and processes in Alaska. As with all models, the Connectivity Project models are most useful when users are aware of the methods used in generating them and the potential errors associated with the model inputs. Thus, we have tried to make these data and methods as transparent as possible. Information not included in this report or in the Technical Addenda can be obtained by contacting the project P.I.s (Appendix A).

Connectivity Project results cannot be used as exact indicators of future biome locations or future species presence/absence data. However, we hope that they provide a useful springboard for planning and research, and for open discussions regarding modeling change and development of Alaska’s habitats and species.

The Connectivity Project model outputs can be used as a guide for field research design for projects intended to investigate related issues. For example, Connectivity

Project results indicate that Alaska marmots and similar relic endemics at high altitudes may be at high risk. A logical follow-up would involve tracking number and ranges of marmots or other high altitude species, using past and present data. Connectivity Project biome shift results indicated that the Western Tundra biome may be at the greatest risk for habitat loss statewide. This finding might inform decisions to pursue further monitoring of climate and vegetation change in this region.

Connectivity Project data can also be linked to existing knowledge about species/climate interactions, in order to select new species to track more closely. For example, any invasive species that is currently limited in its spread by cold winter temperatures may be a prime candidate for closer study.

We recognize that the results presented here are a first but significant milestone in a sustained research effort that should expand and refine our understanding of the connections between rapid climate change, landscape change, redistribution of individual species, and effective ways to promote conservation at a landscape scale. By demonstrating proof of concept for using downscaled GCMs, existing biological and spatial data, and analytical software to model connectivity now and into the future for biomes and single species, we have laid an early foundation for the development of a conservation strategy for adapting to rapid climate change in Alaska. Perhaps the most unique aspect of this project is the incorporation not only of spatial stepping stones (refugia) across Alaska into a conservation design, but temporal stepping stones (transitional states) based on a landscape responding to rapid climate change.

We show in this study that Random Forests™ can be a robust and useful modeling approach for defining the climatic niche of biomes, vegetation, and single species. This modeling approach has simple data requirements when compared with more complex mechanistic models. We successfully modeled nodes (e.g., refugia) and other areas of conservation interest with Marxan. However, none of the modeling methods we considered, including least-cost path analysis using Circuitscape, moving-windows analysis, or landscape metrics (Fragstats), were able to connect these nodes in a meaningful way to show a complete statewide conservation reserve design. We were forced to resort to the “crayon” method, where we connected Marxan hexagons by eye to meet our design criteria.

Many anticipatory adaptation options to rapid climate change, such as extinction triage, translocation of species to places they have never occurred before, or substitution of genetically modified organisms, involve high ecological and societal risks. Taking these risks demands a high degree of certainty in model outputs. However, the difficulty of assessing model uncertainty, particularly when multiple modeling approaches, assumptions, and data sets are being used to depict a reasonable conservation reserve design that incorporates predicted future outcomes, proved to be complex and may be difficult to standardize. We suspect that the convergence of multiple models may ultimately be the most meaningful measure of certainty (or the absence of it).

We deliberately chose to model climate change effects on four species with disparate life histories to demonstrate proof of concept: an ungulate important to subsistence living (caribou), a Beringia relict (Alaska marmot), a migratory bird (trumpeter swan), and an

exotic, invasive plant (reed canary grass). However, one of the other significant selection criteria was that statewide spatial data not only existed but were accessible, which turned out to be a significant constraint as we shopped around for reasonable data sets with which to model species distributions. Furthermore, we found that ancillary data for modeling these species distributions either needed to be derived or were not available. For example, we recognized that reed canary grass was likely to spread rapidly downstream of road crossings, but were unable to model stream flow direction from existing hydrologic data sets and DEMs, although such data layers are now becoming available. We recognized that trumpeter swan distribution may be constrained by competition with tundra swans, but were unable to find a complete data set of the latter with which to model. Although caribou are one of the most studied animals in Alaska, we had to compile several data sets to develop a composite statewide distribution. Finally, the absence of “alpine” as a type in several land cover classifications constrained the robustness of the Alaska marmot models.

Issues of scale and uncertainty are important to consider in modeling species. The inclusion of just a few additional training points to establish the existing climate envelope for a species with very few known occurrence points, such as the Alaska marmot, may greatly expand or narrow the climate envelope used for future modeling. There is also a question about how species occurrence-point data are best linked to climate models that run on global or statewide scales.

The predictions generated by this effort could be assessed and/or improved using 1) more detailed land cover or biome maps; 2) additional data on species distributions, characteristics, and constraints; 3) additional climate data; or 4) different modeling methods. Based on the previous discussion, we offer these suggestions for next steps:

- A valuable next step would be to assess our results further by approaching similar questions using new perspectives, different modeling techniques, and/or alternate data. While we can never truly assess a predictive model until the future becomes the present, we can have more confidence in the models if multiple techniques predict essentially the same response. From a technical standpoint, we also need better methods to display and assess uncertainty.
- Further compilation of species-distribution data, and refinement of these data to reflect seasonality, movement and dispersal, and even productivity, would strengthen the predictive model results.
- The most obvious form of assessment for existing predicted distributions would come from corroboration with individuals who have immediate familiarity with the species and landscapes in question. This would include field biologists and researchers, but would also include those living in village communities around the state, particularly individuals who are frequently engaged in subsistence activities and who are already observing changes associated with altered climate. Traditional ecological knowledge might also identify and designate biomes desired for sustaining traditional ways of life. Further work on this type of modeling for conservation will be greatly enhanced by local involvement.

- There are several avenues for further research at the level of individual species, species communities, and biomes. The current Connectivity Project biome-shift analysis was constrained, given the lack of reliable land-classification data available during the project's time frame. Alaska's ecosystems cannot really be adequately captured in six—or even twelve—biome categories. Improved existing biomes could be developed using AVHRR land cover classes for Alaska and Canada, and cluster analysis methodology. One promising avenue would be to compare modern modeling and clustering techniques (i.e., confusion matrix, Kappa, and other approaches) to produce future predictive distribution maps for many different species.
- The effort just described might be undertaken in conjunction with species distribution mapping done by the Alaska Gap Analysis Project (AK-GAP). The species assessed in the Connectivity Project served only as initial examples, and generated wider interest and discussion about creating a species atlas similar to avian atlases in California and the northeastern U.S. In the long term, an offshoot from this project might be a comprehensive atlas of current and potential future distributions for terrestrial vertebrate species for Alaska. Predictive models of the current distribution for 450 terrestrial vertebrate taxa are under development by the AK-GAP (www.akgap.info).
- Another important step would be to expand all the models used in the above analysis, using a wider range of climate input data. For example, including spring and fall temperature and precipitation as well as values for summer and winter might help distinguish biomes or vegetation units that differ most in the shoulder seasons. During the last workshop of the Connectivity Project partners, there was consensus that the development of robust biome shift projections for Alaska was an important next step in creating tools for conservation planning. This step has now been funded by the U.S. Fish and Wildlife Service and is underway as of spring 2010. Re-running models has the added benefit of checking for consistency and errors. Such verification is important considering the large number of model runs that were produced during this two-year exercise.
- The output data provided by Random Forests™ or other models include tools to define uncertainty by selecting areas where the model assigned the greatest confidence in its ranking selections. Climate envelopes from the current and future prediction areas could be evaluated to look at how significant the departures were in different regions of future predicted ranges. This would allow biologists to determine potential climatic thresholds that may be important in determining species persistence in current locations. In all instances, forecasts will still require biological validation. Use of historic field data to assess modeled backcasting with historic climate data (see section on SNAP climate models) may give insights on the credibility of forecasting.
- Critical temperature thresholds for particular species could be used as a modeling constraint. For example, data are currently available that define temperature

thresholds at which moose exhibit thermal stress. Using this type of data to define the climate envelope for species of concern would be a useful analysis in the future.

- The culmination of developing potential biome shift models and potential shifts in species distribution would be to apply these tools to an Alaska-wide climate change adaptation plan. As we demonstrated using the Marxan models with only four landscape objectives, it is possible to use tools such as Marxan to identify areas that are likely to experience the largest ecological shifts, and conversely, those that may prove the most resilient. This assessment may prove useful to planners in multiple sectors, including agriculture, natural resources development, management of fish and wildlife, and infrastructure development.
- Mechanistic studies are critical to advancing our understanding of climate change and dealing with its consequences appropriately. A more detailed understanding of how species interact with climate is needed if realistic models of future effects are to be achieved. Mechanistic validation of model results would help boost confidence in using long-range models as management tools. The challenge is integrating slow changes over large scales (i.e., climate, which is changing over decades to centuries) with fast changes over small scales (i.e., harvest management and predator-prey cycles, which change annually or biennially). This might include risk analysis, statistical definition of uncertainty, and analysis of the costs and benefits associated with correct and incorrect predictions and associated management decisions.
- Despite the challenges mentioned, we believe it is worthwhile to continue discussions and plans for a statewide conservation-reserve network that allows for the natural migration of flora and fauna in response to a changing climate. This group could form the nucleus of a larger task force, appointed by the Alaska Climate Change Executive Roundtable, tasked with goals similar to the Western Governor's *Wildlife Corridors and Crucial Habitat Initiative*, and in cooperation with the U.S. Department of Interior's development of Landscape Conservation Cooperatives.

The participants in the Connectivity Project recognize that these results are only a first step. Continued research efforts may continue to expand and refine our understanding of the connections between climate change, landscape change, effects on individual species, and effective conservation efforts.

**CONNECTING
ALASKA LANDSCAPES
INTO THE FUTURE**

FINAL REPORT • AUGUST 2010

Appendices and Technical Addenda

Project Participants

This document represents the views of the principal investigators and not necessarily all of the workshop participants. While we attempted to incorporate all of the comments and feedback received from our partners, not everyone was able to comment.

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* Denotes participant who provided comments on this document and/or other substantial contribution.

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Alaskan Biome and Canadian Ecozone Descriptions

The biome descriptions below are adapted from “Home is Where the Habitat is—An Ecosystem Foundation for Wildlife Distribution and Behavior”: http://www.nsf.gov/pubs/2003/nsf03021/nsf03021_2.pdf. This article was prepared by Page Spencer, Gregory Nowacki, Michael Fleming, Terry Brock, and Torre Jorgenson, and was in turn based upon “Narrative Descriptions for the Ecozones of Alaska and Neighboring Territories,” by G. Nowacki, P. Spencer, T. Brock, M. Fleming, and Torre Jorgenson.

The Canadian ecozone descriptions are based on Narrative Descriptions of Terrestrial Ecozones and Ecozones of Canada provided by Environment Canada: <http://www.ec.gc.ca/soer-ree/English/Framework/NarDesc/>

Alpine

The Alpine biome was derived solely for the Connectivity Project, and was based on elevation, rather than directly from the work of Nowacki et al. (2001). As such, it occurs in scattered patches across the mountain ranges of the state. Under the influence of ongoing climate change, the Alpine biome is expected to become increasingly limited to higher elevations, but not to shift spatially across the landscape.

The biome includes steep angular summits with rubble, scree, and remnant glaciers. Where vegetation occurs, alpine tundra and barrens dominate, and soils are thin and rocky. Blueberry-rich alpine tundra gives way to the harsh conditions at the highest elevations, leaving these areas to bare rock, talus, and ice.

Alpine tundra habitats of sedges, grasses, and low shrubs support mountain goats, hoary marmots, and ptarmigan. Populations of Dall sheep and pikas can be found on mid and upper slopes. Caribou, wolves, and brown bears sometimes range into alpine areas.

Arctic

Climate conditions in this northernmost biome are cold and dry. Permafrost is nearly continuous throughout the region, contributing to saturated organic soils in the summer and a variety of freeze-thaw ground features such as pingos, ice-wedge polygons, and oriented

thaw lakes. The Arctic biome includes mountain foothills, as well as coastal plains covered by a vast mosaic of lakes, braided rivers, and wetlands. High-energy stream systems cut narrow ravines in the mountains and coalesce into large braided rivers in the foothills.

Tundra and low-shrub communities predominate throughout the Arctic. Saturated soils and numerous thaw lakes support wet sedge tundra in drained lake basins, swales, and floodplains; tussock tundra and alpine tundra are dominated by sedges and *Dryas* on gentle ridges. Vegetation on lower hill slopes is dominated by mixed shrub-sedge tussock tundra, interspersed with willow thickets along rivers and small drainages and *Dryas* tundra on ridges. Lower and more southerly and easterly mountain slopes and valleys are covered with sedge tussocks and shrubs; and sparse spruce, balsam poplar, and birch forests and tall shrublands occur in larger protected valleys.

Fish are sparse in the mountains, but at lower elevations, arctic char, arctic grayling, arctic cisco, broad whitefish, least cisco, and Dolly Varden are all common. Huge herds of caribou migrate to the Arctic annually. Wolves, arctic foxes, and grizzly bears follow and prey on caribou herds, subsisting on voles, lemmings, arctic ground squirrels, or vegetation when caribou are not available. Muskoxen are re-establishing themselves from introduced animals. Dall sheep inhabit high elevations. Several species of whales migrate into the Arctic Ocean via the Bering Strait in summer, and seals and polar bears are year-round residents. Dense concentrations of lakes and ponds support many species of nesting birds, including a wide variety of shorebirds, ducks, geese, swans, and songbirds, and the rare arctic loon. Bears, snowy owls, arctic foxes, and hares are common. Millions of seabirds (cormorants, kittiwakes, murres, puffins, and auklets) and marine mammals (northern fur seals, ribbon seals, and sea lions) inhabit offshore islands during the summer. Domestic reindeer have been introduced to Nunivak Island and the Seward Peninsula.

Western Tundra

The Western Tundra biome is dominated by a moist sub-polar climate, but summers are sufficiently long and warm to allow patches of stunted trees to grow, primarily along rivers and streams. However, summer warming is tempered by the cold prevailing winds off the Bering Sea. Valleys are filled with finger lakes, while the Yukon-Kuskokwim Delta and the Bristol Bay lowlands are composed of layers of glacial, alluvial, and marine sediments that form low-lying saturated soils and a mosaic of ponds, sloughs, and wandering streams. Permafrost is nearly continuous on the Yukon-Kuskokwim Delta, becoming patchy further south in Bristol Bay. The mountain units have thin rocky soils with sporadic permafrost in the valleys.

Vegetation patterns generally follow the terrain. Conifer species are not present throughout much of this region, though white spruce and balsam poplar grow in stands along many river systems in the eastern edge of this region. Paper birch forests and tall-shrub communities of dwarf birch and alder grow on gently rolling side slopes. Black spruce can be found on some of these sites on the eastern side of this region where it transitions with the Boreal ecoregion. The higher elevations are covered with shrub tundra and lichens or barrens on the wind-scoured summits. Lowlands are covered with a rich

and productive mix of emergent wetlands and sedge-tussock and sedge-moss bogs, with willows along small streams. Slight rises support low shrublands and scattered spruce.

The river systems of this division are incredibly productive for various fisheries, including Bristol Bay sockeye, king, red, and chum salmon. The lake and wetland systems, particularly of the Yukon-Kuskokwim Delta, support millions of staging and nesting waterfowl and shorebirds. Great numbers of walrus and sea lions haul out on rocky beaches, while seabirds patrol the skies. Caribou, wolves, and black and grizzly bears roam the uplands, and moose are continuing to expand their range westward, following tall shrubs and birch forests.

Alaska Boreal

The Alaska Boreal region is characterized by a continental climate, with extreme weather conditions ranging from long, cold winters to short, warm summers. The continental climate is fairly dry throughout the year, and forest fires are frequent during summer droughts. The resulting vegetation pattern is a constantly shifting mosaic of successional communities in response to wildfire and river changes. Permafrost is discontinuous in the southern regions of the Alaska Boreal biome becoming continuous in the northern zones. Soils are underlain by ice-rich permafrost and are subject to thermokarsting, where ice lenses melt or form under insulating moss mats. The boreal forest of Alaska is vegetated with black spruce, tamarack, and paper birch woodlands; shrubby muskeg on permafrost-rich areas; white spruce and balsam poplar on floodplains where permafrost is missing or very deep; and aspen, birch, and shrub on upland areas of recent fires and discontinuous permafrost. The highly productive vegetation along major rivers supports vigorous stands of white spruce and balsam poplar. Robust wet sedge meadows and aquatic vegetation are invading sloughs and oxbow ponds. The adjacent permafrost-dominated lowlands support black spruce woodlands, dwarf birch and low-growing ericaceous shrubs of the heath family, and sedge-tussock bogs.

The climate in the boreal lowlands becomes progressively more continental the further east one travels, as the temperature ranges become greater and precipitation decreases. Permafrost is continuous to the north of this biome, and discontinuous south and west of it.

Boreal lowlands are pockmarked with lakes and ponds, which support tremendous concentrations of nesting waterfowl and other migratory birds, and an abundance of moose, bears, furbearers, northern pike, and salmon. Large rivers support important runs of chinook, chum, and coho salmon, while clear tributary streams support Dolly Varden and grayling. These areas support large populations of moose and black bear, abundant waterfowl during breeding and molting seasons, furbearers, including beavers, muskrats, and martins, as well as ravens and raptors, such as peregrine falcons.

Boreal uplands are primarily vegetated by white spruce, birch and aspen on south-facing slopes, and black spruce on north-facing slopes. Uplands are subject to frequent forest fires. Caribou, moose, snowshoe hares, marten, lynx, and black and brown bears are plentiful.

Boreal Transition

The climate of the Boreal Transition biome has shorter winters than the continental interior, and warmer, drier summers than the marine-influenced coastal rainforests. However, the Alaska Range generates its own weather, as moisture-laden air rises over the massif and releases heavy snowfalls on the upper elevations. Remnants of glaciers and many glacial features define the landscape. Boreal forests are distributed in the valleys and lowlands of the division, but wildfire and permafrost have much less influence on vegetation succession and distribution.

Glacial rivers are silty and braided, with broad, gravelly floodplains. Clear streams are generally smaller with narrower floodplains. Arctic grayling are common in clear mountain streams, and all five species of Pacific salmon migrate into rivers of the Boreal Transition. Soils in the mountainous units of the Alaska Range and Lime Hills are generally thin, rocky, and cold, with scattered pockets of permafrost. The Copper River Basin floor has fine-grained saturated soils with ice-rich permafrost. Soils of the Cook Inlet Basin are a complex mixture of alluvial, glacial, volcanic, and lacustrine materials with occasional patches of permafrost. Both basins support boreal vegetation patterns, with white spruce and birch on higher ground and black spruce, low shrubs, sedges, and mosses growing in the wetlands. White spruce and balsam poplar form successional stands along the rivers. The lower slopes of the Alaska Range and Talkeetna Mountains are covered with dense thickets of alder that transition to low shrubs in the subalpine.

The wide variety of habitats supports many species of mammals and both resident and migratory birds. Golden eagles, ptarmigan, ravens, Dall sheep, mountain goats, wolverines, caribou, moose, grizzly and black bears, wolves, foxes, lynx, beavers, and various small mammals can be found within this region. Waterfowl nest in the wetlands of the basins, although not in the concentrations found in the Yukon-Kuskokwim Delta or Yukon Flats.

North Pacific Maritime

The North Pacific Maritime biome, along the north and east shores of the Gulf of Alaska, receives copious rain at lower elevations and snow at higher altitudes, coupled with relatively warm temperatures throughout the year. The warm, wet climate supports lush conifer rainforests along the coast and large ice fields and glaciers at higher elevations. The coastlands reflect their glacial heritage, with steep bedrock fjords, tidewater glaciers, and numerous rocky islands.

A few areas along this coast remained ice-free during one or more glacial advances, providing refugia for plant and animal species. Soils are exceptionally thin except in riparian zones. Relatively warm winters preclude permafrost. Five species of Pacific salmon migrate into the steep, fast-flowing streams to spawn, and in the process, cycle tremendous amounts of nutrients back to the freshwater and terrestrial systems. Dolly Varden, char, and steelhead (ocean-going rainbow) trout live in larger clear-water streams.

The warm maritime environment encourages lush moss-draped conifer forests along the coast. Old-growth forests of Sitka spruce, hemlock, and cedar blanket the lower slopes

of the Alexander Archipelago. Toward the west, cedar ceases in Prince William Sound, and hemlock reaches to the end of the Kenai Peninsula. On Kodiak, Sitka spruce is expanding south across the island into new habitats. Pockets of wetlands have formed on shallow, poorly drained soils on bedrock throughout the division. Coves and rocky islands are fringed with intertidal communities of kelp, eelgrass, and barnacles. Upper forests give way to a narrow subalpine zone of alder and herbaceous meadows and then alpine tundra and bedrock or ice.

Common forest animals include black and brown bears and Sitka black-tailed deer. Offshore waters are rich with deepwater fish such as halibut and cod. Grey and humpback whales migrate along the coast. Bald eagles, common murre, Bonaparte's gulls, Steller's sea lions, harbor seals, and sea otters are common.

Aleutian Islands

The Aleutian Islands biome is defined by cool, moist, and harsh weather. Permafrost is absent, reflecting the relatively warm climate, dominated by oceanic influences. Soils are a mixture of volcanic materials, often reworked by glacial and alluvial agents. Areas of recent glaciations and volcanic activity are largely barren cinder plains. Other parts of the region, well watered by Pacific storms and fertilized by nesting seabirds, support lush meadow and heath vegetation communities, with willows along streams. The flora is a blend of species from two continents, grading from Asian to North American affinities from west to east.

This biome is the domain of seabirds, waterfowl, and marine mammals. Sea otter populations, which rebounded from near extirpation by Russian and American fur traders, have recently experienced population declines. Endangered Steller's sea lions use low rocky shelves as haulouts and pupping areas, although their numbers have dropped dramatically within the past several decades. Several species of whales reside here or migrate through, en route to the Arctic Ocean. Caribou, which are native on the peninsula and Unimak Island, have been introduced to several Aleutian Islands. Foxes, introduced to many islands for fox farming, and rats, introduced accidentally from ships, have nearly decimated ground-nesting waterfowl, including the Aleutian cackling goose. Fox eradication and careful reintroduction on several islands of the Aleutian cackling goose have resulted in recent removal of this bird from the endangered species listing and increased nesting success for seabirds. New efforts to eradicate rats show promise for rebuilding seabird populations on additional islands.

Boreal Cordillera Ecozone

The Boreal Cordillera ecozone is located in the midsection of the cordilleran system. It covers sections of northern British Columbia and the southern Yukon. The climate ranges from cold, subhumid to semiarid, and is marked by long, cold winters and short, warm summers, modified by vertical zonation and aspect. Mean annual temperatures range from 1°C to

5.5°C. The coldest mean annual temperatures occur in the Yukon Plateau region. The mean summer temperatures range from 9.5°C to 11.5°C. Mean winter temperatures range from -13°C to -23°C. The Pacific maritime influence moderates temperatures over most of the ecozone. Mean annual precipitation is lowest in valleys within the rain shadow of the coastal ranges (<300 mm) and increases in the interior ranges further east, where up to 1500 mm of precipitation is received at higher elevations. Precipitation in the intermontane plateau areas ranges 300–600 mm annually.

In some parts of this ecozone (British Columbia), there are grasslands on south-facing slopes with boreal forest vegetation on the north-facing slopes, a feature unique within the boreal forests of Canada. The vegetative cover ranges from closed to open canopies over much of the plateaus and valleys. Tree species include white and black spruce, alpine fir, lodgepole pine, quaking aspen, balsam poplar, and white birch. In the northwest, the stands are generally open, and lodgepole pine and alpine fir are usually absent. At higher elevations, there are extensive areas of rolling alpine tundra characterized by sedge-dominated meadows, and lichen-colonized rock fields are common.

This ecozone is characterized by mountain ranges that contain numerous high peaks and extensive plateaus, separated by wide valleys and lowlands. The area has been modified by glaciation, erosion, solifluction, and eolian and volcanic ash deposition. Glacial drift, colluvium, and outcrops constitute the main surface materials. Only a small portion of this ecozone in the northwest was unglaciated. Permafrost and associated landscape features tend to be widespread in the more northerly areas and at higher elevations; soils are cryosolic in these regions. In the warmer, lower elevations in the southern half, brunisols, podzols, and luvisols are common.

Mammals of the Boreal Cordillera ecozone include woodland caribou, moose, Dall sheep, mountain goat, black and grizzly bear, marten, lynx, American pika, hoary marmot, and arctic ground squirrel. Representative bird species include willow, rock and white-tailed ptarmigan, and spruce grouse, along with a range of migratory songbirds and waterfowl.

Taiga Cordillera Ecozone

The Taiga Cordillera ecozone is located along the northernmost extent of the Rocky Mountain system and covers most of the northern half of the Yukon and southwest corner of the Northwest Territories. In this ecozone are found Canada's largest waterfalls, deepest canyons, and wildest rivers.

Annual precipitation ranges from less than 300 mm in the north to over 700 mm in the southeast (Selwyn Mountains). Mean annual temperatures range from -10°C in the north to -4.5°C in the south. Mean summer temperatures, which range from 6.5°C to 10°C, are modified by vertical zonation and aspect. Summers are warm to cool with extended periods of daylight. Mean winter temperatures range from -25°C in the north to -19.5°C in the south. Winters are long and cold with very short daylight hours. Weather patterns from the Arctic and Alaskan coasts have a marked influence on this ecozone.

Natural vegetation ranges from arctic tundra (dwarf or low shrubs, mosses and lichens, and cottongrass) in the north, to alpine tundra (dwarf shrubs, lichens, saxifrages, and mountain avens) in higher elevations, and taiga or open woodland in the south (white spruce and white birch), mixed with medium to low shrubs (dwarf birches and willows), mosses, and lichens.

Steep, mountainous topography, consisting of repetitive, sharply etched ridges and narrow valleys, predominates with foothills and basins present. The bedrock is largely sedimentary in origin with minor igneous bodies. Much of the area is mantled with colluvial debris, with frequent bedrock exposures and minor glacial deposits. The northwest portion of this ecozone consists of unglaciated terrain. Brunisols, regosols, and cryosols tend to be the predominant soils. Most wetlands, which in some ecoregions are extensive, are underlain by permafrost. Abundant permafrost features, such as peat hummocks, palsas, and peat plateaus, are common in peatlands. The unglaciated portions of this ecozone commonly exhibit periglacial features such as cryoplanation terraces and summits and various forms of sorted and unsorted patterned ground. Continuous permafrost underlies most of the ecozone with the exception of the western half of the Mackenzie and Selwyn Mountains ecoregions.

Wildlife in the area is diverse. Characteristic mammals include Dall sheep, woodland and barren-ground caribou, moose, mountain goat, black and grizzly bear, wolf, lynx, arctic ground squirrel, American pika, hoary marmot, and a large concentration of wolverine. Important birds include gyrfalcon, willow and rock ptarmigan, and waterfowl. Most of the area remains a wilderness. The Yukon's Old Crow Flats is a large wetland complex that has received international recognition for its value to swans, Canada geese, and other waterfowl species that nest or stage here in the tens of thousands each year.

Pacific Maritime Ecozone

The Pacific Maritime ecozone covers the mainland Pacific coast and offshore islands of British Columbia. The wettest climates in Canada occur in this coastal ecozone, especially near the mountains on the windward slopes of Vancouver Island, the Queen Charlotte Islands, and the mainland Coast Mountains.

The climate of this ecozone ranges from relatively mild humid maritime at low elevations to cool very humid at higher elevations in the main mountain systems. The ecozone has some of the warmest and the wettest climatic conditions in Canada. Mean annual temperatures range from 4.5°C in the north to 9°C in the Georgia-Puget Basin–Lower Mainland regions. The mean summer temperature ranges from 10°C in the north to 15.5°C in the south. Mean winter temperatures range from –0.5°C to 3.5°C. Relative to the rest of Canada, there is little variation between mean monthly temperatures throughout the year. Annual precipitation ranges from as little as 600 mm in the Gulf Islands of lower Strait of Georgia to over 4000 mm in the Coastal Gap region to the north. Overall, the zone typically receives 1500–3000 mm of precipitation per year. The Pacific maritime influence is responsible for the high level of precipitation and for the temperature moderation.

The temperate coastal forests are composed of mixtures of western red cedar, yellow cedar, western hemlock, Douglas-fir, amabilis fir, mountain hemlock, Sitka spruce, and alder. Many of these trees reach very large dimensions and grow to great ages, forming ancient or old-growth forests of this ecozone. Douglas-fir is confined largely to the extreme southern portion of the ecozone. In the north, amabilis fir becomes more common. Mountain hemlock is usually associated with higher elevations. Variations in altitude account for the presence of widely contrasting ecosystems within the ecozone, ranging from mild, humid coastal rainforest to cool boreal and alpine conditions at higher elevations.

Mountainous topography dominates, cut through by numerous fjords and glacial valleys and bordered by coastal plains along the ocean margin. Igneous and sedimentary rocks underlie most of the area. Colluvium and glacial deposits are the main surface materials. The soils are largely podzolic and brunisolic. The Queen Charlotte Islands and part of Vancouver Island that escaped glaciation are unique, because they now contain many endemic species—ones that are peculiar to those habitats. Ice-free coastal waters are associated with the narrow continental shelf and slope.

Characteristic mammals include black-tailed deer, black and grizzly bear, elk, wolf, otter, and raccoon. Bird species unique to this area of Canada include American black oystercatcher, California and mountain quail, tufted puffin, and chestnut-backed chickadee. Other representative birds are pygmy-owl, Steller's jay, and northwestern crow. Marine environments are typified by northern sea lion, northern fur and harbor seal, and giant beaked, sperm, grey, killer, Pacific pilot, and blue whale. Salmon and associated spawning streams are located throughout this ecozone. Freshwater discharge from coastal rivers mixing with ocean waters stimulates the occurrence of abundant marine life.

Montane Cordillera Ecozone

Most of southern British Columbia and a portion of southwestern Alberta are contained within the Montane Cordillera ecozone—the most diverse of all the ecozones, ranging from alpine tundra to dense conifer forests to dry sagebrush and grasslands. There are some large, deep lakes and major river systems, including the Fraser River and the Columbia River headwaters.

The climate of the region ranges from subarid to arid and mild in southern lower valleys to humid and cold at higher elevations in the northern reaches. Moist Pacific air and the effect of orographic rainfall control the precipitation pattern such that both rain shadows and wet belts are generated within the ecozone, often in close geographic proximity to each other. The rain shadow cast by the massive Coast Mountains results in some of the driest climates in Canada in the valley bottoms of the south-central part of the ecozone. The Rocky Mountains also impede the westward flow of cold continental arctic air masses. Mean annual temperatures range between 0.5°C in the northwest (Skeena Mountains) to 7.5°C in the Okanagan area along the Canada–United States border. Mean summer temperatures range from 11°C to 16.5°C. The mean winter temperatures range from –11°C

to -1°C . Annual precipitation is 1200–1500 mm in the mountains and ranges to the west, to 500–800 mm in the north and interior, rising again to 1200 mm in the mountains and ranges along the British Columbia-Alberta border. Precipitation falls below 300 mm in the arid valleys and plateaus to the south.

Vegetative cover is extremely diverse; alpine environments contain various herb, lichen, and shrub associations, whereas the subalpine environment has tree species such as lodgepole pine, alpine fir, and Engelmann spruce. With decreasing elevation, the vegetation of the mountainous slopes and rolling plains separates into three general groups: a marginal band of forests characterized by Engelmann spruce, alpine fir, and lodgepole pine; forests characterized by ponderosa pine, interior Douglas-fir, lodgepole pine, and trembling aspen in much of the southwest and central portions; and forests characterized by western hemlock, western red cedar, interior Douglas-fir, and western white pine in the southeast. Shrub vegetation found in the dry southern interior includes sagebrush, rabbitbrush, and antelope bush. Most of the natural grasslands that existed in the dry south have vanished, to be replaced by urban settlement and agriculture.

The Montane Cordillera ecozone is a rugged, mountainous unit that incorporates several major interior plains. The plains are more extensive in the north and extend as intermontane valleys toward the southern half of the ecozone. Most of these plains and valleys are covered by glacial moraine and, to some degree, fluvial and lacustrine deposits, whereas the mountains consist largely of colluvium and rock outcrops. Luvisols and brunisols are the most common soils, with podzols occurring in the mountain ranges in the wetter eastern portion of the ecozone. The soils of the lower valley floors to the south are often chernozems and support grasslands. These soils grade into arid environments in the Okanagan area toward the Canada–United States border.

Characteristic mammals include woodland caribou, mule and white-tailed deer, moose, mountain goat, California bighorn sheep, coyote, black and grizzly bear, hoary marmot, and Columbian ground squirrel. Typical bird species include blue grouse, Steller's jay, and black-billed magpie.

Taiga Plains Ecozone

The Taiga Plains are located mainly in the southwesterly corner of the Northwest Territories, northeastern British Columbia, and northern Alberta. Taiga, a Russian word, refers to the northern edge of the boreal coniferous forest—that Land of Little Sticks which spans from the subarctic of Labrador to Alaska and beyond, from Siberia to Scandinavia. The ecozone is dominated by Canada's largest river, the mighty Mackenzie, and its tributaries. It is bordered in the west by cordilleran mountain ranges, to the east by two huge lakes (the Great Slave and Great Bear), to the north by extensive Mackenzie Delta, and to the south by the closed forests of the Boreal Plains ecozone.

The climate is marked by short, cool summers and long, cold winters. Cold arctic air influences the area for most of the year. The mean annual temperature ranges between -10°C in the Mackenzie Delta region to -1°C in Alberta and British Columbia. From

north to south, the mean summer temperature ranges from 6.5°C to 14°C. The mean winter temperature ranges from –26°C in the north to –15°C in the south of the ecozone. Snow and freshwater ice persist for six to eight months of the year. The mean annual precipitation is low, ranging from 200 to 500 mm.

The ecozone is characterized by open, generally slow-growing conifer-dominated forests of predominantly black spruce. The shrub component, which is often well developed, includes dwarf birch, Labrador tea, and willow. Bearberry, mosses, and sedges are dominant understory species. Upland and foothill areas and southerly locales tend to be better drained, are warmer, and support mixed-wood forests characterized by white and black spruce, lodgepole pine, tamarack, white birch, trembling aspen, and balsam poplar. Along the nutrient-rich alluvial flats of the larger rivers, white spruce and balsam poplar grow to sizes comparable to the largest of these species in the boreal forests to the south.

This ecozone is the northern extension of the flat Interior Plains, which dominates the Prairie and Boreal Plains ecozones to the south. The subdued relief of broad lowlands and plateaus are incised by major rivers, the largest of which can show elevational differences of several hundred meters. Underlain by horizontal sedimentary rock—limestone, shale, and sandstone—the nearly level to gently rolling plain is covered with organic deposits and, to a lesser degree, with undulating to hummocky morainal and lacustrine deposits. Alluvial deposits are common along the major river systems, including braided networks of abandoned channels. Low-lying wetlands cover 25–50% of the zone. A large portion of the area is underlain by permafrost, and this acts to perch the surface water table and promote a regional overland seepage system. When combined with low-angle slopes, permafrost creates a landscape that is seasonally waterlogged over large areas. Patterned-ground features are common. The region's widespread permafrost and poor drainage create favorable conditions for cryosolic, gleysolic, and organic soils.

Characteristic mammals include moose, woodland caribou, wood bison, muskox, wolf, black bear, marten, lynx, and arctic ground squirrel. Barren-ground caribou overwinter in the northwest corner of this ecozone. Bird species include the common redpoll, gray jay, common raven, red-throated loon, northern shrike, sharp-tailed grouse, and fox sparrow. Fish-eating raptors include the bald eagle, peregrine falcon, and osprey. The Mackenzie Valley forms one of North America's most travelled migratory corridors for waterfowl (ducks, geese, and swans) breeding along the Arctic coast.

Boreal Plains Ecozone

The Boreal Plains ecozone extends as a wide band from the Peace River country of British Columbia in the northwest to the southeastern corner of Manitoba. Unlike the neighboring Boreal Shield, this ecozone is not bedrock-controlled, has few bedrock outcrops and considerably fewer lakes.

The climate is typified by cold winters and moderately warm summers, and is strongly influenced by continental climatic conditions. The mean annual temperature ranges between –2°C and 2°C. Mean summer temperatures range between 13°C and 15.5°C.

Mean winter temperatures range from -17.5°C to -11°C . Winter temperatures in the foothills of Alberta are a few degrees warmer. Mean annual precipitation rises from 300 mm in northern Alberta to 625 mm in southwest Manitoba. The average annual growing season ranges 1000–1250 growing degree-days above 5°C .

White and black spruce, jack pine, and tamarack are the main coniferous species. Broadleaf trees, particularly white birch, trembling aspen, and balsam poplar, are most numerous in the transitional section leading to the prairie grasslands. Black spruce and tamarack increase in dominance along the northerly sections of the ecozone.

Underlain by Cretaceous shales, this nearly level to gently rolling plain consists largely of hummocky to kettled glacial moraine and lacustrine deposits. The surface materials are usually deep and tend to mask the underlying topography. The soils of this ecozone are largely luvisols, which grade southward into black chernozems and northward into brunisols and organics. Wetlands, including peatlands with organic soils cover between 25% and 50% of the ecozone.

Characteristic mammals include woodland caribou, mule and white-tailed deer, moose, wapiti (elk), coyote, black bear, marten, fisher, lynx, and chipmunk. Representative birds include boreal and great horned owl, blue jay, rose-breasted and evening grosbeak, Franklin's gull, red-tailed hawk, and northern harrier. Pelican, cormorant, gull, heron, and tern are most prominent in this ecozone. The whooping crane, perhaps Canada's most famous endangered species, nests in wetlands of Wood Buffalo National Park at the extreme north of the ecozone.

Derivation of SNAP Climate Projections

As described in the report, the Connectivity Project used climate model outputs provided by the Scenarios Network for Alaska Planning (SNAP). These models provided mean monthly precipitation and temperature projections for future decades. Their derivation is described below.

General Circulation Models (GCMs) are the most widely used tools for projections of global climate change over the timescale of a century. Periodic assessments by the Intergovernmental Panel on Climate Change (IPCC) have relied heavily on global model simulations of future climate driven by various emission scenarios. The IPCC uses complex coupled atmospheric and oceanic GCMs. These models integrate multiple equations, typically including surface pressure; horizontal layered components of fluid velocity and temperature; solar short-wave radiation and terrestrial infrared and long-wave radiation; convection; land surface processes; albedo; hydrology; cloud cover; and sea ice dynamics.

General Circulation Models include equations that are iterated over a series of discrete time steps as well as equations that are evaluated simultaneously. Anthropogenic inputs such as changes in atmospheric greenhouse gases can be incorporated into stepped equations. Thus, GCMs can be used to simulate changes that may occur over long time frames because of the release of excess greenhouse gases into the atmosphere.

Greenhouse-driven climate change represents a response to radiative forcing that is associated with increases of carbon dioxide, methane, water vapor, and other gases, as well as associated changes in cloudiness. The response varies widely among models because it is strongly modified by feedbacks involving clouds, the cryosphere, water vapor, and other processes whose effects are not well understood. Thus far, changes in radiative forcing associated with increasing greenhouse gases have been small relative to existing seasonal cycles. Hence, the ability of a model to accurately replicate seasonal radiative forcing is a good test of its ability to predict anthropogenic radiative forcing.

Different coupled GCMs have different strengths and weaknesses, and some can be expected to perform better than others for northern regions of the globe. John Walsh et al. (2008) evaluated the performance of a set of fifteen global climate models used in the Coupled Model Intercomparison Project. Using the outputs for the A1B (intermediate) climate change scenario, Walsh et al. calculated the degree to which each model's output concurred with actual climate data for the years 1958–2000 for each of three climatic

variables (surface air temperature, air pressure at sea level, and precipitation) for three overlapping regions (Alaska only, 60–90° north latitude, and 20–90° north latitude.)

The core statistic of the validation was a root-mean-square error (RMSE) evaluation of the differences between mean model output for each grid point and calendar month, and data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis, ERA-40. The ERA-40 directly assimilates observed air temperature and sea level pressure observations into a product spanning 1958–2000. Precipitation is computed by the model used in the data assimilation. The ERA-40 is one of the most consistent and accurate gridded representations of these variables available.

To facilitate GCM intercomparison and validation against the ERA-40 data, all monthly fields of GCM temperature, precipitation, and sea level pressure were interpolated to the common 2.5° × 2.5° latitude/longitude ERA-40 grid. For each model, Walsh et al. calculated RMSEs for each month, each climatic feature, and each region; then added the 108 resulting values (12 months × 3 features × 3 regions) to create a composite score for each model. A lower score indicated better model performance.

The specific models that performed best over the larger domains tended to be the ones that performed best over Alaska. Although biases in the annual mean of each model typically accounted for about half of the models' RMSEs, the systematic errors differed considerably among the models. There was a tendency for the models with the smaller errors to simulate a larger greenhouse warming over the Arctic, as well as larger increases of arctic precipitation and decreases of arctic sea level pressure, when greenhouse gas concentrations were increased.

Since several models had substantially smaller systematic errors than the other models, the differences in greenhouse projections implied that the choice of a subset of models might offer a viable approach to narrowing the uncertainty and obtaining more robust estimates of future climate change in regions such as Alaska. Thus, SNAP selected the five best-performing models out of the fifteen: ECHAM5 (Germany), GFDL2.1 (United States), MIROC3.2 (Japan), HADLEY3 (UK), and CGCM3.1 (Canada). These five models are used to generate climate projections independently, as well as in combination, to further reduce the error associated with dependence on a single model.

Because of the enormous mathematical complexity of GCMs, they generally provide only large-scale output, with grid cells typically 1°–5° latitude and longitude. For example, the standard resolution of HadOM3 is 1.25° in latitude and longitude, with 20 vertical levels, leading to approximately 1,500,000 variables.

Finer-scale projections of future conditions are not directly available. However, local topography can have profound effects on climate at much finer scales, and almost all land management decisions are made at much finer scales. Thus, some form of downscaling is necessary to make GCMs useful tools for regional climate change planning.

Historical climate-data estimates at 2 km resolution are available from PRISM (Parameter-elevation Regressions on Independent Slopes Model), which was originally developed to address the lack of climate observations in mountainous regions or rural areas. PRISM uses point measurements of climate data and a digital elevation model to

generate estimates of annual, monthly, and event-based climatic elements. Each grid cell is estimated via multiple regression, using data from many nearby climate stations. Stations are weighted based on distance, elevation, vertical layer, topographic facet, and coastal proximity.

PRISM offers data at a fine scale useful to land managers and communities, but it does not offer climate projections. Thus, SNAP needed to link PRISM to GCM outputs. This work was done by John Walsh, Bill Chapman, et al. They first calculated mean monthly precipitation and mean monthly surface air temperature for PRISM grid cells for 1961–1990, creating PRISM baseline values. Next, they calculated GCM baseline values for each of the five selected models using mean monthly outputs for 1961–1990. They then calculated differences between projected GCM values and baseline GCM values for each year out to 2099 and created “anomaly grids” representing these differences. Finally, they added these anomaly grids to PRISM baseline values, thus creating fine-scale (2 km) grids for monthly mean temperature and precipitation for every year out to 2099. This method effectively removed model biases while scaling down the GCM projections.

Based on this small-scale grid, SNAP offers statewide maps, available as Google Earth (KML) or GIS (ASCII) files, of mean monthly temperature and precipitation based on each of the five selected models and the means of all five (composite model). All of these maps are available for three different emissions scenarios, described by the IPCC: The A2 scenario assumes a heterogeneous world with high population growth and slow economic and technological change. The B1 scenario assumes a global population that peaks in mid-century and rapid change toward a service and information economy. The A1B scenario falls between these two, and assumes rapid economic growth, a global population that peaks in mid-century, rapid introduction of technologies that are more efficient, and a balance between fossil fuels and other energy.

SNAP models were assessed by generating model runs for past time periods and then analyzing the statistical relationship between real weather patterns and model outputs. GCM output for dates in the past is not linked in any way to historical weather station data. Hence, this validation provides an excellent means for characterizing both the strengths and weaknesses of the models. However, we can expect that even the best model data will match real data only in terms of mean values, variability between seasons, variability between years, and long-term trends; not in day-to-day values.

SNAP compared GCM output to historical weather station data based on four different metrics: monthly mean values, seasonal (month-to-month) variability, annual (year-to-year) variability, and long-term climate change trends. Each of these comparisons was performed with both temperature data and precipitation data. Each of the analyses was based on data from 32 Alaska weather stations for the period 1980–2007. Data were obtained from the Western Region Climate Center. The requirement for selection of a climatic station was that no more than 5% of the monthly values could be missing.

Overall, SNAP models performed well when analyzed for concurrence with measured climate data with respect to monthly mean values, seasonal variability, annual variability, and long-term climate change trends. In general, SNAP models mimicked real weather

patterns less accurately for precipitation than for temperature. This may be due to the innate variability of precipitation across space and time.

In cases where generating mean values are more important than capturing climate variability, using a composite of all five models is likely to yield the most robust results. Of the three available emissions scenarios, true emissions seem to be following a pattern somewhere between the A2 (pessimistic) and A1B (midrange) scenarios. Thus, to select a conservative approach, the composite model for the A1B scenario was used for the Connectivity Project.

Given that the six Alaska biomes derived from Nowacki et al. (2001) do not capture the ecological conditions unique to steep elevational gradient that occurs in high mountains, we created a seventh biome defined by elevation and location as well as by climate envelope. Unlike pixels in other biomes, we reasoned that alpine zones cannot shift north or south across the landscape, but are locked to the mountain ranges in which they occur. Based on the literature (Körner and Paulsen 2004), we estimated that alpine zones would shrink upward by over one meter per year, or as much as 150 meters by the end of the century.

We encountered difficulties when attempting to define accurately all current alpine zones in the state. Tree line is reached at different elevations for mountain ranges at different latitudes and different longitudes, making it impossible to easily extrapolate alpine zones from existing data sets. We expected to address this problem by using training data from all different ranges and, potentially, to incorporate a latitudinal stratification. To map the Alpine biome (in addition to the six Alaska biomes already described), we first obtained maps of known alpine regions. Unfortunately, no comprehensive map of all such areas was available, and we were limited to data for three separate regions around the state. We used maps for the Denali region, the Kenai Peninsula, and the Ez7071 region defined in the LANDFIRE project, which includes much of the Brooks Range (LANDFIRE 2010). To represent the transition of expanding tree line with time, we added elevation as a variable, using DEM data. We then simulated this movement by modeling tree line rise for each biome-shift time step. We modeled a rise of 40 m by 2039, 80 m by 2069, and 150 m by 2099 (Juday et al. 1999; Kullman 2000). While promising, the Alpine zones shown in Figure II-1 are incomplete, omitting mountain ranges in the northwestern and southeastern parts of the state, among other regions. These results were too limited to be incorporated into other modeling efforts, but they help illustrate potential change and the need for an alpine geospatial data layer for the state of Alaska.

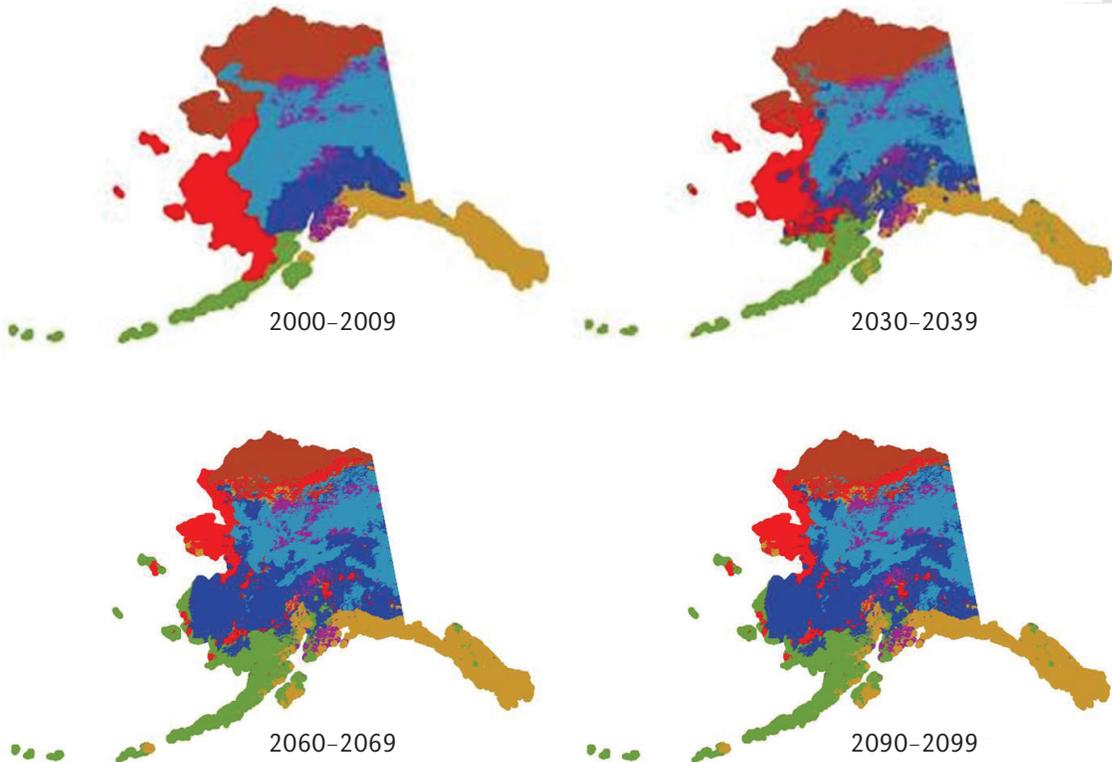


Figure II-1 – Projected change in the Alpine zone over time. The Alpine biome, which is shown in purple and overlaid on the other six Alaska biomes, is projected to rise 150 meters in elevation by 2099, thus markedly decreasing in total area.

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LANDFIRE Mapping of Units 70 and 71 (ez7071)

Although the LANDFIRE vegetation mapping project was not complete at the time we undertook this first stage of the Connectivity Project, we tested two units for which complete land cover data were already available in draft form—units 70 and 71, located in the Brooks Range.

In this region, map legends were consistent across grouped map zones approximating our biomes. However, the classification system used by LANDFIRE in this area included 46 classes, with 6 non-vegetated classes, at a spatial resolution or pixel size of 30×30 meters.

Although Random Forests™ works with many variables/classes, our sample sizes (number of pixels per class) would have been too low with all 46 classes. Thus, we regrouped them into 20 classes (Table III-1). For example, grouping all seven alpine classes together and bundling all four wetland types were easy combinations. It should be noted that different class combinations would lead to different results.

In grouping these categories into a smaller number, to provide better statistical data for Random Forests™, we encountered a few difficulties. For example, recently burned areas were lumped into one “Recently burned forest and woodland” class, regardless of what forest type they might eventually return to. White and black spruce were in distinct classes.

Next, we resampled data into a 5 km lattice and derived a climatic envelope (temperature and precipitation) for each of the 20 classes. We used climate projections, as in the biome modeling exercise, to find the best-fitting climatic envelope for each 5 km grid square for future dates. We then matched these new climatic envelopes with the corresponding vegetation types in units 70 and 71.

While Random Forests™ can be used to fit LANDFIRE vegetation classes statewide, based on this small training area, the results are obviously unrealistic, as can be seen in Figure III-1. There is too little climate variability in units 70 and 71 to provide adequate training for regions as diverse as the Aleutians, the Arctic, and Southeast Alaska. Thus, the resulting map shows large areas of single vegetation types (generally representing more generalist species and cover types), in contrast to the high spatial variability of the training area. Nevertheless, this approach may prove worthwhile when statewide training data are available and have been assessed for accuracy.

Table III-1: Grouping of the original LANDFIRE classes into 20 land cover classes for modeling.

LANDFIRE CLASS NAME	Connectivity Combined Group #
Open Water	1
Perennial Ice/Snow	2
Developed, Low Intensity	3
Developed, Medium Intensity	3
Barren	4
Recently Burned Forest and Woodland	5
Western North American Boreal White Spruce Forest	6
Western North American Boreal Tree line White Spruce Woodland	6
Western North American Boreal Spruce-Lichen Woodland	7
Western North American Boreal White Spruce-Hardwood Forest	7
Western North American Boreal Mesic Black Spruce Forest	7
Western North American Boreal Mesic Birch-Aspen Forest	8
Western North American Boreal Dry Aspen-Steppe Bluff	8
Western North American Boreal Subalpine Balsam Poplar-Aspen Woodland	9
Alaska Sub-boreal Avalanche Slope Shrubland	10
Alaska Sub-Boreal Mesic Subalpine Alder Shrubland	10
Western North American Boreal Mesic Scrub Birch-Willow Shrubland	11
Western North American Sub-boreal Mesic Bluejoint Meadow	11
Western North American Boreal Active Inland Dune	4
Western North American Boreal Montane Floodplain Forest and Shrubland	12
Western North American Boreal Lowland Large River Floodplain Forest and Shrubland	12
Western North American Boreal Riparian Stringer Forest and Shrubland	13
Western North American Boreal Shrub and Herbaceous Floodplain Wetland	13
Western North American Boreal Herbaceous Fen	14
Western North American Boreal Sedge-Dwarf-Shrub Bog	14
Western North American Boreal Low Shrub Peatland	15
Western North American Boreal Black Spruce Dwarf-tree Peatland	15
Western North American Boreal Black Spruce Wet-Mesic Slope Woodland	16
Western North American Boreal Black Spruce-Tamarack Fen	16
Western North American Boreal Deciduous Shrub Swamp	17
Western North American Boreal Freshwater Emergent Marsh	17

Western North American Boreal Wet Meadow	17
Western North American Boreal Freshwater Aquatic Bed	17
Western North American Boreal Low Shrub-Tussock Tundra	18
Western North American Boreal Tussock Tundra	18
Western North American Boreal Wet Black Spruce-Tussock Woodland	18
Western North American Boreal Alpine Dwarf-Shrub Summit	19
Western North American Boreal Alpine Mesic Herbaceous Meadow	19
Western North American Boreal Alpine Dryas Dwarf-Shrubland	19
Western North American Boreal Alpine Ericaceous Dwarf-Shrubland	19
Western North American Boreal Alpine Dwarf-Shrub-Lichen Shrubland	19
Western North American Boreal Alpine Floodplain	19
Alaska Sub-boreal and Maritime Alpine Mesic Herbaceous Meadow	19
Alaska Sub-boreal White-Lutz Spruce Forest and Woodland	20
Alaska Sub-boreal White Spruce-Hardwood Forest	20



Figure III-1 – Extrapolating statewide, based on vegetation classifications for units 70 and 71. As can be seen from this figure, it is highly unrealistic to use climate envelope modeling to extrapolate vegetation shift outside the “training zone” used by Random Forests™, since where there is no good fit, results show a few vegetation categories dominating across broad areas.

Defining Biomes and Modeling Biome Shifts in Random Forests™

Reconciling Canadian and Alaskan data

The biomes used for this project were derived from the Unified Ecoregions identified by Nowacki et al. (2001), and from the six Canadian ecozones described in detail in Appendix C. However, since the data available for these ecozones were not entirely congruent with the data available for Alaska, some adjustments had to be made to effectively model ecozones and biomes together.

The six Alaska biomes were defined by biophysical characteristics rather than by land area and, therefore, varied in size. The six Canadian ecozones also varied in size and were within roughly the same size range, so could be considered congruent in this sense (Figure 2). However, our Alaska climate data from SNAP were all available at 2 km resolution, as described in the report. Climate data for ecozones were available only as mean values for each ecoregion within an ecozone, offering much lower resolution than the Alaska data.

To get around this problem, we overlaid a 2 km grid on the Canadian data, and assigned values to each grid cell based on the ecoregion in which it fell. We downloaded the data in GIS format from the following websites:

- http://sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.html (The National Ecological Framework for Canada GIS data sets, providing ecozones and ecoregions as shapefiles) and
- http://climate.weatheroffice.ec.gc.ca/Welcome_e.html (Canada's National Climate Data and Information Archive, providing historical GIS data for cities and ecoregions based on 1971–2000 normals).

Thus, every pixel in an ecozone would be assigned climate values for the ecoregion in which it occurred, giving Canadian data the same weight as Alaskan data, from the point of view of Random Forests™ climate-envelope modeling. This approach introduced some degree of unavoidable error, however, since the mean values for ecoregions would be far less likely to contain outliers than the individual pixel values for Alaska. In other words, the Alaska climate-envelope data for each biome had a much greater range and standard deviation than the Canadian data.

Since Random Forests™ assigns pixels to future climate envelopes based on mean values and best fit, outliers should not be of great concern. Pixels that are atypical for a particular biome will have little effect in the projected movement of that biome. However, the greater variability in the Alaska data may have played a role in cases where the model had trouble finding any best fit among the available biome choices.

A perhaps more important source of error implicit in this technique arises from the fact that the Canadian “baseline” data were derived from climate normals of actual weather station data for the years 1971–2000. The Alaska baseline data, on the other hand, used model projections for the decade 2000–2009. Thus, the two data sets are both temporally separated and based on different methodologies. The SNAP modeled data, when assessed by SNAP, perform similarly to weather station data for Alaska. However, the different times for the baseline may play a significant role in the definition of “current” climate envelopes, thus skewing results.

Defining climate envelopes in a continuous landscape

Although Alaska biomes and Canadian ecozones are based on identifiable ecological areas, there is invariably some overlap between the species cohorts present and other characteristics of each biome, particularly at the boundaries. Likewise, there is overlap between biomes, and high variability within biomes, in the expected climate variables used as model inputs (mean June and December mean temperature and precipitation). How, then, can we make landscape predictions based on the relationship between climate variables and biome classifications?

Random Forests™ is able to deal with the inherent fuzziness of the data through repeated sampling. The model grows many classification trees (many trees creating a “forest”) from training data. The model then randomly samples multiple training cases, with replacement at each run. A random sample of a subset of input variables is chosen at each node to define the best split (branch). Each tree is grown to the largest extent possible (with no pruning of data). Finally, the best classification (best match) is chosen from among all the trees grown. There are several advantages to this method. First, the model does not overfit the training data. Second, it automatically estimates the importance of input variables. Thus, if some input variables make very little difference in the outcome of the model (which match is selected as the best), they will be given very little weight. In addition, unused training data allow cross-validation for an unbiased estimate of the classification error, meaning there is no need to create separate categories of data to reserve for validation.

As described in the body of the report, for this pilot effort we created a 5 km grid by resampling the original 2 km data, in order to reduce the number of pixels and thus the overall time for each modeling run. In all, our analysis included approximately 120,000 pixels.

Literature cited

Nowacki, G., P. Spencer, M. Fleming, T. Brock, and T. Jorgenson (2001). Ecoregions of Alaska: 2001. U.S. Geological Survey Open-File Report 02-297 (map).

Caribou Modeling by Herd or Season

At the start of the Connectivity Project, caribou biologists cautioned that generalized climate-envelope modeling would be challenging, given the highly adaptive nature of the species and their tendency to periodically alter their preferred habitat locations. Their predictions proved accurate, though we believe that the total range analysis provided in the body of the text does add value to understanding potential changes in response to global climate change. This technical addendum describes the modeling approaches attempted and the lessons learned through the process. Our initial intent in modeling caribou was to examine their ranges on a herd-by-herd and seasonal basis. However, it quickly became clear that distribution data for caribou in Alaska are variable, with many herds being represented solely by a coarse “total range” polygon. This coarse distribution data further limited our ability to develop appropriate climate-envelope metrics. Ideally, distribution for winter range, summer range, and calving areas would all be included.

Our next approach was to cluster the herds into northern and southern groups, and examine summer and winter ranges in this combined format. Northern herds tend to be large and migrate long distances in arctic habitats. About 75% of the total estimated harvest in Alaska (primarily by subsistence users) comes from the four northern herds, which are all migratory to some extent and calve on the coastal plain or the adjacent northern foothills of the Brooks Range at roughly similar latitude. In contrast, southern herds cover a wide range of habitats (interior to coastal) over a broad range of latitude. Southern herds vary from tiny sedentary groups to a few migratory herds that have irrupted (e.g., Mulchatna) and even an insular herd at Adak in the Aleutian Islands, which was transplanted from Nelchina stock. We excluded the Adak herd (non-typical habitat) from analysis to avoid strong geographic leveraging of the spatial models. Relatively few herds had winter ranges defined, compared with summer ranges (Table V-1).

We used Random Forests™ to predict future summer and winter ranges for northern and southern herds based on climate envelopes. Of the 33 herds for which there is some level of range use defined, there were two northern herds (Central Arctic and Western Arctic) and two southern herds (Mulchatna and Nelchina) where summer and winter ranges were identified independently (Table V-1). We used the contemporary ranges of these four herds to calibrate the herd range predictions associated with future climate envelopes (Figure V-1). These exercises reinforced the need for sufficient and appropriate

spatial data for this type of predictive model.

The results of this mapping effort showed a decline in range size for northern and southern herds in the winter and for northern herds in the summer, but an increase in range size for southern herds in the summer. While these results were thought-provoking, a wide range of variables were left unaccounted for, and we could not readily explain the loss of summer habitat in the Arctic shown in the combined winter- versus summer-range predictive model (Figures V-2 and V-3). Because of the small sampling area to define winter habitat ranges for caribou in Alaska, it became increasingly apparent that the best approach, given data available today, is to base predictions on combined herd ranges rather than seasonal shifts (Figure 18). In the future, it might be best to derive a climate envelope from global caribou distribution, to better represent the adaptability of this species.

Table V-1: Seasonal ranges (updated 2008) used in modeling differences in northern and southern caribou herds in Alaska.

Herd	Geography	Summer	Winter
Central Arctic	Northern	Y	Y
Porcupine	Northern	Y	
Teshkepuk	Northern	Y	
Western Arctic	Northern	Y	Y
Beaver Mountains	Southern	Y	
Chisana	Southern	Y	
Delta	Southern	Y	
Denali	Southern	Y	
Farewell-Big River	Southern	Y	
Fortymile	Southern	Y	
Fox River	Southern		Y
Galena Mountain	Southern	Y	
Kenai Lowlands	Southern	Y	
Kenai Mountains	Southern		Y
Macomb	Southern	Y	
Mentasta	Southern	Y	
Mulchatna	Southern	Y	Y
Nelchina	Southern	Y	Y
Northern Peninsula	Southern	Y	
Nushagak Peninsula	Southern	Y	
Rainy Pass	Southern	Y	
Ray Mountains	Southern	Y	
Southern Peninsula	Southern	Y	
Sunshine Mountains	Southern	Y	
Tonzona	Southern	Y	
Twin Lakes	Southern		Y
Unimak	Southern	Y	
White Mountains	Southern	Y	
Wolf Mountain	Southern	Y	

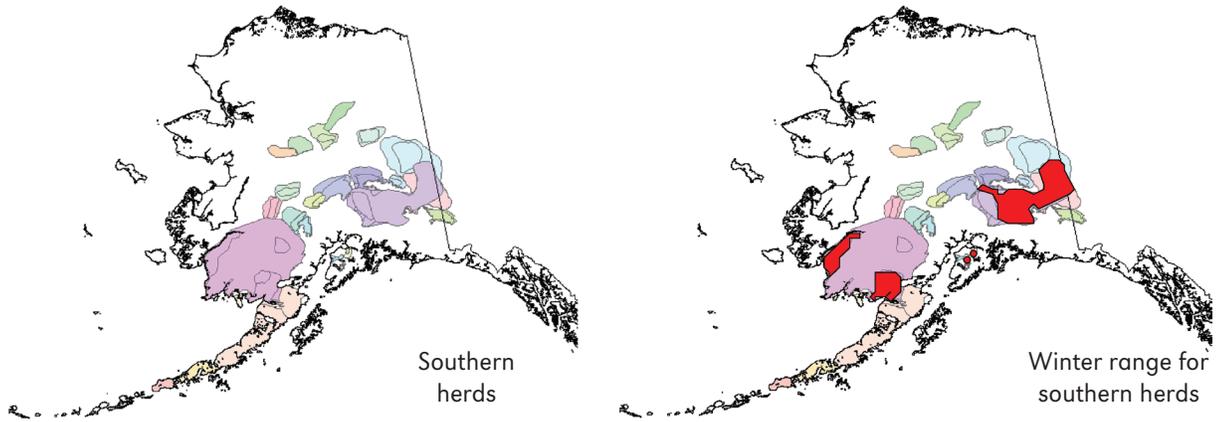


Figure V-1 – Available range information for southern herds in 2008.

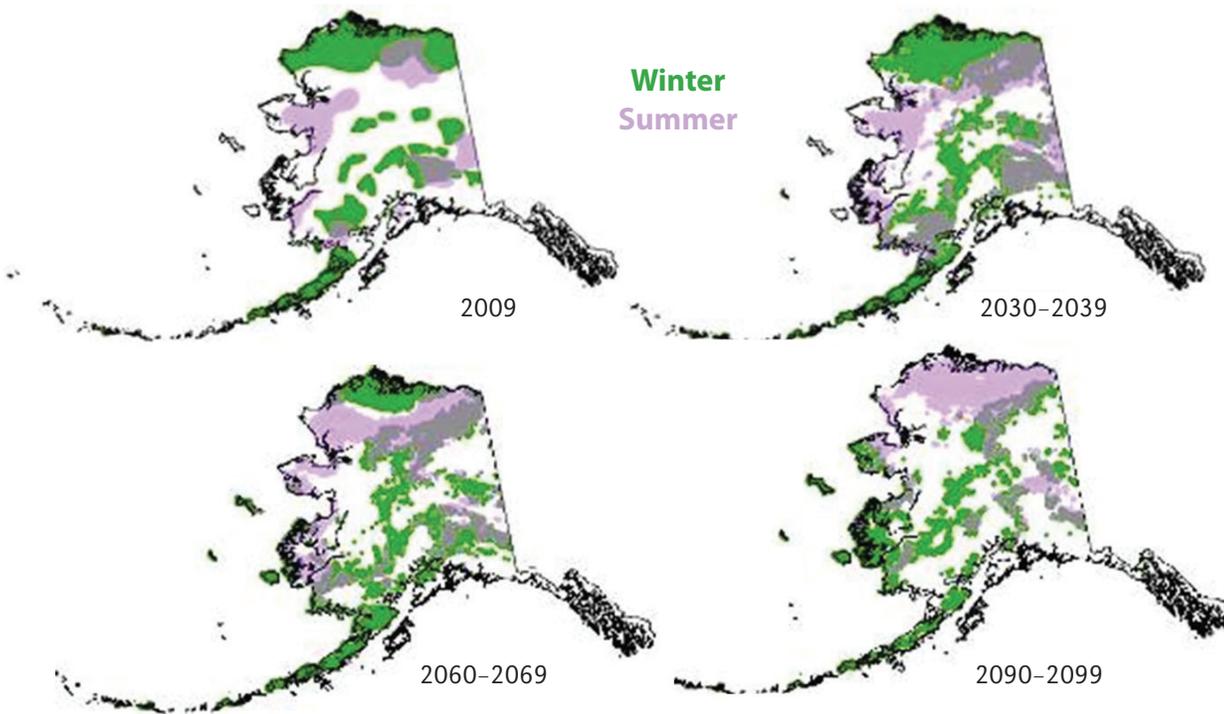


Figure V-2 – Projected caribou range for all herds combined. Although caribou are expected to persist statewide, climate modeling indicates that ranges may shrink, particularly summer ranges in the Arctic.

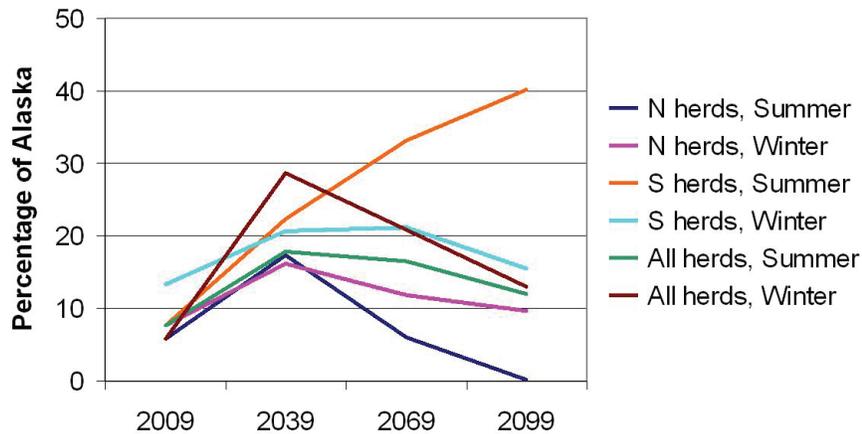


Figure V-3 – Range size of all herds as a percentage of the state. Overall, this analysis, based on only a portion of total caribou range areas, suggests a 64% decrease in summer range and a 47% decrease in winter range.

How does climate directly and indirectly affect caribou movements? Temperature thresholds may impact physiology, disease, parasites, and icing events that reduce available forage, and long-term climate change may impact habitat and available forage, which in turn impacts fitness. The Boreal ALFRESCO model developed by UAF is designed to predict how fire and vegetation will change with climate. The ALFRESCO model was used to predict winter habitat for the Nelchina caribou herd (Rupp et al. 2006), so we considered combining the models. Because the two modeling approaches rely on the same climate data, it seemed reasonable to use the ALFRESCO results for good winter caribou habitat as a filter over the winter herd climate-envelope results. This exercise produced a further decrease in available habitat; however, because we determined that winter caribou-range data in the Random Forests™ approach were too narrow, none of those results is shown here.

Literature cited

Rupp T.S., M. Olson, L.G. Adams, B.W. Dale, K. Joly, J. Henkelman, W.B. Collins, and A.M. Starfield (2006). Simulating the influences of various fire regimes on caribou winter habitat. *Ecological Applications* 16:1730–1743.

Potential climate effects on Alaska marmots are largely unknown, although studies on yellow-bellied marmots that occupy high-elevation habitats in Colorado have shown marked climate change impacts on hibernation (Inouye et al. 2000). Our modeling efforts were based on a series of facts, hypotheses, and assumptions taken from the literature (Gundersen et al. 2009) and from expert participants in our workshops:

- Alaska marmots occur in the Brooks Range as well as in more southerly and westerly mountain ranges in Alaska. In more southern regions of the state, competition occurs between the Alaska marmot and the hoary marmot (*Marmota caligata*), but it is unclear whether they have non-overlapping ranges, and if so, where the boundary lies between the subspecies.
- Alaska marmots are generally found only in alpine areas; however, “alpine” is poorly defined in Alaska, and is not available as a distinct GIS layer.
- Marmots are generally found only in areas of “rough” terrain, i.e., where there are steep slopes and plenty of open rocks for cover.
- Known occurrences of Alaska marmots (Figure VI-1) are likely to under-represent the true range of the species’ habitat.
- Warming climate would tend to cause alpine zones to shrink through vegetative encroachment.
- Warming climate might have some positive impacts on marmot survival, through greater survival during overwintering, although changes in snowpack might reduce area of denning habitat, and peak area generally declines when habitats move to higher elevations.

Based on the criteria just listed, we first attempted to model shifts in marmot habitat based on our model of changes in the Alpine zone (see Technical Addendum II, Modeling the Alpine Biome). However, this proved unsatisfactory due to the uncertainties inherent in our estimated Alpine distribution. Because we were almost certainly missing large areas of alpine terrain, we were likely to be under-representing marmot habitat. In addition, as can be seen in Figure VI-1, known occurrences of marmots do not perfectly match modeled alpine zones. This may be because our Alpine biome was missing data from several mountain ranges, or it may be because “Alpine” includes large areas of snow and ice, typical at the highest elevations, as well as the type of terrain preferable to marmots (rocky and high elevation, but not ice-bound year-round).

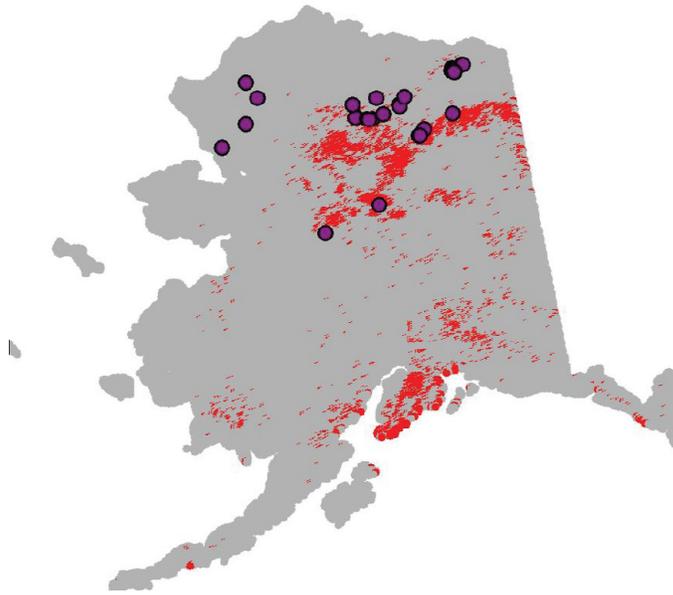


Figure VI-1 – Known Alaska marmot occurrences overlaid with modeled Alpine zone model.

Thus, in later modeling efforts we shifted to a new map layer to constrain potential marmot habitat: terrain roughness (Figure VI-2). Terrain roughness was calculated based on digital elevation mapping (DEM). Terrain is considered “rough” where the change in elevation and slope from one pixel to the next is high. Therefore, roughness can be loosely equated with variable steepness and variable aspect—typical of rocky slopes and summits.

When known occurrences of marmots were overlain with areas of high terrain roughness (Figure VI-3), a good match was found. Using roughness as a parameter enabled us not only to constrain the potential habitat of marmots in our future predictions, but also to expand it within current and future time periods. In other words, we recognized that the scattered points available as verified marmot sightings do not encompass all locations at which marmots are likely to be found. Coupling DEM roughness with a climate envelope allowed us to avoid grossly overestimating the species’ likely range, while still generalizing and extrapolating marmot habitat beyond the limits of these points (Figure VI-3) This approach could prove useful for inventory efforts that seek to locate Alaska marmots.

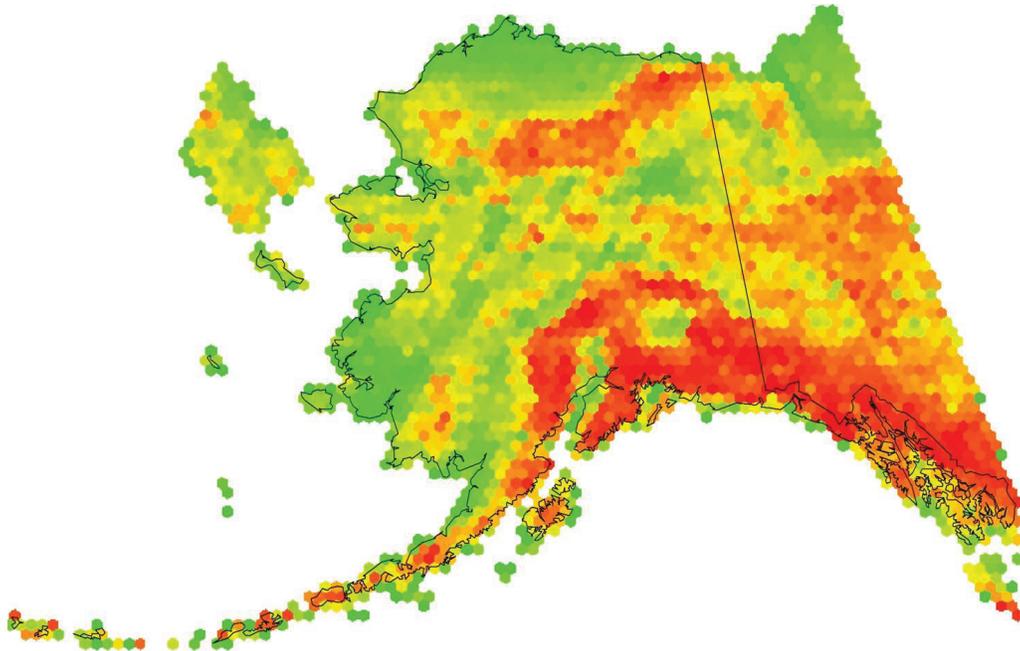
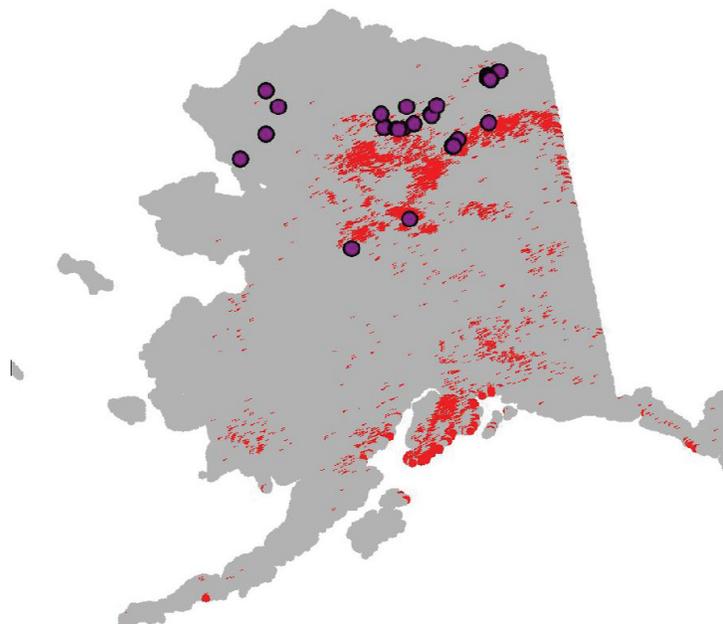


Figure VI-2 – Terrain roughness. Roughness was calculated from DEM data, based on change in slope between adjacent pixels. Note that this metric serves as a good proxy for estimating the presence of mountainous zones (seen in red on this map).



Figures VI-3 – Potential marmot habitat with terrain roughness as a factor. Known occurrences of marmots are overlaid with modeled contemporary habitat.

Our model results predicted significant decrease in marmot habitat over time, as explained in the text. How such change may impact the connectivity of marmot habitat depends on total marmot populations and maximum dispersal distances, as well as the following, calculable from our modeling results:

- Change in total habitat area
- Change in mean patch size
- Change in mean distance between patches
- Change in mean distance to patch of some minimum size
- Percentage of patches (or of total habitat) more than some maximum distance from nearest other patch (i.e., % of isolated habitat)

Further research is needed to determine distributions of existing Alaska marmot populations, the nature and boundaries of competitive exclusion with hoary marmots, dispersal ability, and reproductive capacity. In addition, data on litter size would help to elucidate which habitat types allow for the greatest reproductive success. This exercise also highlighted the need for research on how spatial scales influence uncertainties in climate envelope models. Using 34 point locations to derive a species' climate envelope may be inappropriate, however, it is unclear what level of training data provides an adequate minimum sample for this type of modeling.

Literature cited

Gunderson, A.M., B.K. Jacobsen, and L.E. Olson (2009). Revised distribution of the Alaska marmot, *Marmota broweri*, and confirmation of parapatry with hoary marmots. *Journal of Mammalogy* 90(4):859–869.

Inouye, D.W., B. Barr, K.B. Armitage, and B.D. Inouye (2000). Climate change is affecting altitudinal migrants and hibernating species. PNAS, 2000.

The trumpeter swan data used in our model (Figure VII-1) were provided by Debbie Groves (USFWS – Juneau) via Bob Platte (USFWS – Anchorage), and were based on the 2005 Trumpeter Swan Survey, a census flown every five years in August.

These data were complete within the zone of the survey. However, trumpeter swans were distinguished from tundra swans based on habitat rather than on morphological characteristics, with all swans in forested regions assumed to be trumpeters. Tundra swans were not surveyed. Some tundra swans may have been misidentified as trumpeter swans, and vice versa. No clear information is available to indicate whether competitive exclusion or habitat limitations are responsible for this partitioning of habitat. Based on the available data, it is impossible to guess exactly where the boundary between species lies and how it is likely to shift with climate change, unless we assume that it will shift at the same rate that vegetation (forest) shifts. In our modeling of potential biome shifts, we can only show when the temperature and precipitation patterns are suitable for a forested biome, and not the actual movement of vegetation within each biome. As a proxy for competition with tundra swans, we used the predicted occurrence of a forested biome (Alaska Boreal, Boreal Transition, Boreal Plains, Taiga Plains, Montane Cordillera, Pacific Maritime, or North Pacific Maritime) as a limiting factor (“mask”) when modeling future habitat for this species. In today’s non-forested regions of the state, the expansion of trumpeter swans is likely to be an over estimate of the rate at which they could occupy those areas if the link to forested landscapes is a requirement.

Based on the literature (Bellrose 1980), we determined the following:

- Trumpeter swans re-establish territories as soon as the ice goes out in May or June; they often re-use old nest sites (high nest fidelity) so about 4 days are needed to construct or repair a new nest.
- Trumpeter swans lay an egg every other day until the clutch is complete; mean clutch is 5, so we can assume egg-laying takes 10 days.
- Incubation varies from 33–37 days.
- Cygnet development from hatching to flying takes 13–15 weeks (91–105 days).
- Total time from nest initiation to flying away is 138 to 156 days.

In sum, this implies that 138 ice-free days are needed to fledge cygnets reliably and successfully. Thus, we used SNAP data on ice-free days as a limiting factor (“mask”) for delineation of swan habitat. As noted in the report, SNAP’s estimation of this parameter is

likely to be inexact, but any significant skew in the presumed date of thaw due to lag time between temperatures of about zero and open water is likely to be cancelled out by an equivalent lag in autumn freeze-up.

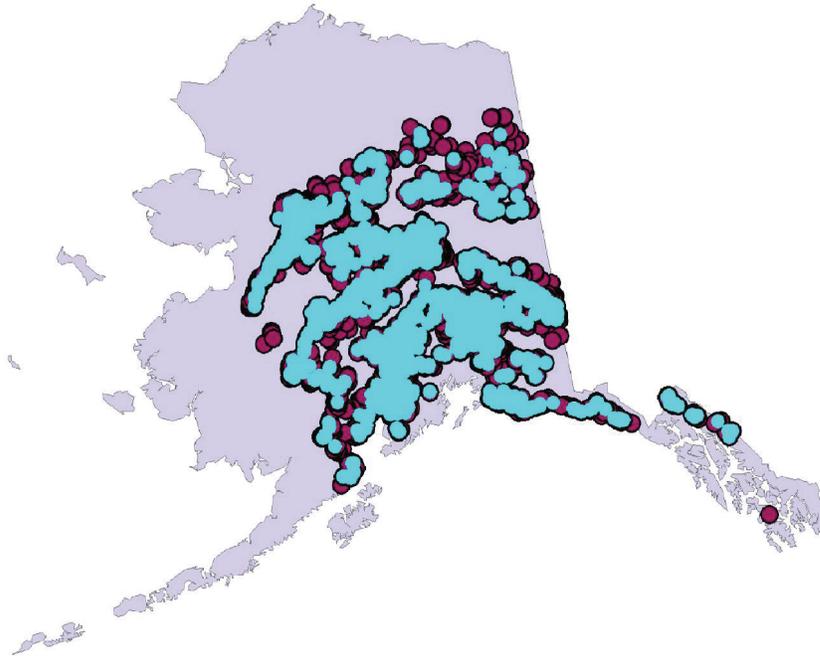


Figure VII-1 – Trumpeter swan sightings, 2005. Purple points indicate sightings of adult swans, and blue points indicate adults with young less than one year old.

In our modeling efforts, we originally attempted to use brood size as a variable, to map not only presence/absence but also reproductive success. Our hope was to be able to find some kind of gradient of reproductive success across the range of climate envelopes in habitat types that would indicate which habitats are optimal and which are marginal. However, initial model runs evidenced no such gradient. There appeared to be no clear links between brood size, climate, and habitat. Therefore, we decided to model based merely on presence/absence.

As described in the report, our results predicted overall spread of trumpeter swan habitat, as forested biomes encroach northward and westward. Further research could help clarify the role of competitive exclusion with tundra swans, as well as the effects of shifting climate and changing habitat on brood size.

Literature cited

Bellrose, E.C. (1980). *Ducks, Geese and Swans of North America*. Harrisburg, Pennsylvania: Stackpole Books.

Derivation of Reed Canary Grass Model

Reed canary grass, which is already well established in southcentral Alaska, is rapidly spreading across the state. The species may be difficult to limit or control, since mechanical removal is labor intensive and no herbicides are selective enough to be used in wetlands without the potential for injuring native species (ANHP 2006).

Reed canary grass has an extremely broad range, and little data exist in the literature on the limitations to range of the grass based on climate factors. Given that the grass is known to disperse along road and river corridors (WRCGMWP 2009), our modeling efforts were based on the climate envelope of existing occurrences of the grass (June and December mean temperature and precipitation) as well as distance to roads (Figure VIII-1).

Existing occurrence of reed canary grass was modeled using data from AKEPIC. Approximately 5,000 records exist for the species, although even this is likely to be a gross underrepresentation of actual occurrence. Most sightings of the grass are recorded near roads and human habitation, and it is almost impossible to determine whether this is because the grass is spread along these corridors, or because no records have been taken from locations that are more far-flung. As with other species, even the best data accounting for the presence of a species are incomplete without data on the species' absence, which are rarely recorded.

Initially, we planned to incorporate distance to rivers also, as a variable analogous to distance to roads. However, this proved problematic for several reasons. First, although GIS layers exist for Alaska water bodies, at the time we were preparing model runs, they were not coded in terms of direction of flow or connectivity between rivers and tributary streams. These data are now being added to publically available GIS files, and might be useful for inclusion in further studies. Moreover, it was unclear how to consider variables such as stream type (glacial, non-glacial, fast or slow moving) and size. Alaska is rich in waterways and wetlands, but without this crucial connectivity data, we found it challenging to incorporate seed transmission along waterways as a variable. We did consider including waterways as a static factor, since the grass occurs almost exclusively along their banks and channels. However, waterways and wetlands are so ubiquitous across the state that including this layer put us at risk of overestimating the spread of the grass.

We also struggled with how to include roads most realistically. In our first iterations of the reed canary grass model, we used the existing road network as our roads layer. Later,

we created new GIS layers to include RS2477 trails (official corridors that may or may not currently be in use) and proposed roads. These roads, although mapped and clearly described in regional DOT plans available online (State of Alaska 2009), are drawn long-hand in existing plans, and did not exist as GIS layers. Thus, we had to create layers using estimates from the existing maps. Since it was not always clear when the proposed roads were expected to be built, we included all new roads in the final (2090s) map projections. For example, in the final decadal step, we added a probable road to Nome, which was supported by the Governor’s office at the time of our modeling, and a few other planned roads from publically available DOT maps. These additions expanded the already increasing range distribution from the 2060s time step especially through the Seward Peninsula (Figure VIII-1).

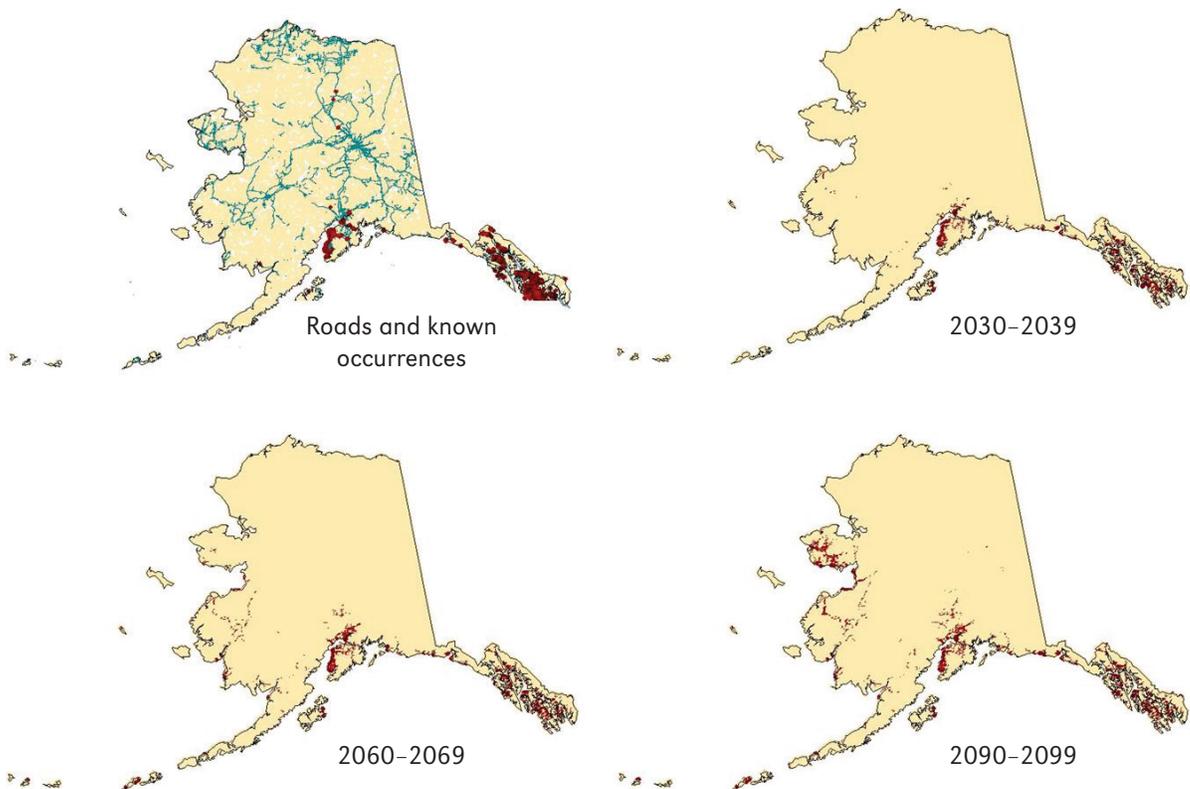


Figure VIII-1 – Grass modeling using a more extensive transportation network. In this model iteration, the spread of reed canary grass was modeled using roads connected to the continental highway system plus projected roads, winter trails, and RS2477 historic trails. However, many of these corridors are seasonal, disconnected, or rarely used.

In our final iteration, in order to address the variable use of trails and seasonal roads, the fact that this network may be disconnected in both space and time, and the uncertainty of proposed roads, we reverted to including only all-season existing roads. Thus, our results

are likely to represent a significant underestimation of potential distribution, based on both a cautious approach to road-based spread and a complete lack of water-assisted spread.

Although the few sampling points along the Dalton Highway were too few to result in a modeled spread into the Arctic, it is clear that the Dalton Highway (Haul Road) could be a bottleneck or a conduit for the spread of reed canary grass into the Arctic, since it serves as a single artery to the south for a large network of winter roads (impassible in summer) associated with oil and gas development across the North Slope. Mitigation to slow the spread of this species and other undesirable invasives might include a truck-wash site or other disinfecting process, as is practiced for contracted equipment entering Denali National Park. Of course, such a measure would require extensive discussion between industry, DOT, and land managers. It will be important to manage the spread of this species along the highway corridor so that it does not become a threat in the Arctic.

Literature cited

ANHP (Alaska Natural Heritage Program) (2006). Non-Native Plant Species of Alaska: Reed canarygrass. Environment and Natural Resources Institute University of Alaska Anchorage. http://akweeds.uaa.alaska.edu/pdfs/species_bios_pdfs/Species_bios_PHAR_ed.pdf

State of Alaska (2009). Statewide and Area Transportation Plans. <http://dot.alaska.gov/stwdplng/areaplans/lrtpp/SWLRTPHome.shtml>

WRCGMWP (Wisconsin Reed Canary Grass Management Working Group) (2009). Reed Canary Grass (*Phalaris arundinacea*) Management Guide: Recommendations for Landowners and Restoration Professionals.

Notes

