Rare Vascular Plant Distributions In Alaska: Evaluating Patterns Of Habitat Suitability In The Face Of Climate Change

Matthew L. Carlson[1] and Helen Cortés-Burns[2]

ABSTRACT

The high magnitude of projected climate change in northern latitudes represents a serious concern to the persistence of Alaskan plant species with limited geographic distributions or narrow habitat requirements. To address this potential vulnerability, we review the distribution patterns of Alaska's rare plants and initial results from current and future habitat suitability models for 34 rare plants. Hotspots of rare taxa in the state are concentrated in the Aleutian Islands, southeastern Alaska, interior Alaska and Brooks Ranges, and the Arctic Coastal Plain. Approximately 60% of Alaska's rare species are found at high elevations, islands, or adjacent to the Arctic Ocean and therefore appear to lack clear migration corridors to track their current climate envelopes under future scenarios. We used inductive habitat-suitability models to evaluate whether future suitable habitat locations would be reduced in size or shifted in location. Preliminary models for rare species with southwestern Alaska and montane distributions showed little change in suitable area. Model outputs for interior species were varied: some models suggest large shifts and others minor shifts in suitable habitat. Last, outputs for arctic endemics suggest a dramatic loss of suitable habitat in 50 years. Species did not have consistent responses to climate variables, but in general, annual precipitation appeared to be a more important driver than mean annual temperature or other variables. This modeling effort highlights the need to identify additional important variables that drive many of Alaska's rarest plants distributions, and the need for experimental approaches for the most at-risk species to understand the relationship of climate warming on population vital rates.

Keywords: Alaska, rare plants, climate change, climatic niche model

INTRODUCTION

Alaska is in the enviable position relative to states and provinces to the south in having very few vascular plants at risk of extirpation. Currently a single plant species is listed as Endangered by the USFWS (Federal Register 1988) and just 24 taxa are listed as globally imperiled to critically imperiled in the state (AKNHP 2012). This low number of species of conservation concern is not solely a function of lower total biodiversity. Total plant species richness of approximately 2,000 species (Hultén 1968) is comparable to other Pacific Northwest states and provinces. However with a significantly larger area, the number of

---

[1] Matthew L. Carlson is an associate professor in the Biological Sciences Department at the University of Alaska Anchorage and program botanist for the Alaska Natural Heritage Program, University of Alaska Anchorage, 707 A Street, Anchorage, Alaska 99501;

[2] Helen Cortés-Burns is a Botanist for the Alaska Natural Heritage Program, University of Alaska Anchorage, 707 A Street, Anchorage, Alaska 99501

rare species per unit area is dramatically less in Alaska relative to other states (e.g., 15.2 × less than Washington). While Alaska does not harbor a large number of globally rare species, it encompasses the limited North American distribution of a number of widespread Eurasian species, such as Oxygraphis glacialis (Fisch.) Bunge, Saussurea triangulata Trautvetter & C. A. Meyer, and Potentilla stipularis L., where the North American distribution of these taxa are limited to a few populations in western Alaska. Additionally, the circumpolar north may harbor numerous cryptic plant species and is suggested to be a region of rapid incipient speciation (Grundt et al. 2006). Thus, we argue that Alaska makes a significant contribution to the plant biodiversity in the North America.

The low number of species at risk of extirpation in Alaska can also be attributed to fewer threats from human development. The primary cause of species endangerment, habitat conversion (Meffe and Carroll 1997, Wilcove and Master 2008), has been considerably less in Alaska relative to other states (e.g., road density is approximately 30 × less in Alaska relative to Washington and 880,000 acres have been converted to agriculture in Alaska relative to 15,000,000 acres in Washington, USDA 2012). Current and proposed large-scale natural resource extraction activities (such as mining and oil and gas development) however are causing alterations to substrates and habitats more broadly, which are likely to increasingly threaten rare plant populations. Second, dramatic changes in climate cause a growing reason for concern. Increases in mean annual temperature are well accepted to be proceeding more dramatically at high latitudes (Serreze et al. 2000) and direct and indirect impacts of climate change have the potential to threaten the persistence of plant species at these latitudes. In just the last 30 years, there has been a +2 °C increase in mean annual temperature in the arctic biome (ACIA 2005) and temperature is predicted to continue to increase more rapidly than at lower latitudes (IPPC 2007). The growing season has nearly doubled in length the interior of Alaska in the last 100 years, from 90 to 170 days (Wendler and Shulski 2009). Species and communities appear to be responding to these changes. There are numerous examples of increases in shrub and tree expansion in arctic and alpine tundra habitats (Klein et al. 2005, Dial et al. 2007, Tape et al. 2006, Roland 2012). As the majority of rare vascular plant species in Alaska are associated with open, low-competition habitats, shrub and tree encroachment represents a serious threat to these rare plant populations. Additionally, climate change is influencing patterns and frequency of disturbances in northern systems, such as increasing the frequency and intensities of herbivorous insect outbreaks and wildfires (Soja et al. 2006, Chapin et al. 2008). Last the rate of non-native plant species introduction and establishment in natural systems is accelerating in Alaska and is likely exacerbated by increased temperatures, longer growing seasons, and more frequent and severe disturbances (Carlson and Shephard 2007). While indirect ecological impacts associated with climate change, such as disturbance and herbivory, are the most difficult to predict and quantify, they are likely to have impacts that are equal or greater than direct impacts (Davis et al. 1998, Klanderude 2005, Suttle et al. 2007, Adler et al. 2009).

Rare plant species in Alaska display pronounced biogeographic patterns. Some of these biogeographic associations are anticipated to experience more extreme climatic changes, and/or lack clear dispersal routes to future suitable climate and are therefore expected to be more vulnerable to climate change. Hierarchical cluster analysis of globally rare to imperiled species by 250,000 mi^2 grid cells and ecogeographic region (Nowacki et al. 2001) suggest these species can be grouped into an Aleutian, southeastern coastal, montane, interior, and Bering Strait, and Arctic Coastal Plain associations (fig. 1). Projected global circulation model average temperatures predict an approximately +2 °C increase over much of Alaska in 50 years, but with greater increases in northern Alaska and only modest increases in southwestern Alaska to the Aleutian Islands (SNAP 2012). Total precipitation is expected to remain relatively similar along the Arctic Coastal Plain, southeastern coast, and in the interior, while southwestern and western Alaska is projected to become significantly wetter. Specifically, we anticipate that Aleutian, montane, and Arctic Coastal Plain species associations are more vulnerable to reduced and geographically disparate future suitable habitats since these species would presumably have to move to the north and to higher elevations to track suitable climates and they are predicted to show the most dramatic changes in temperature or precipitation. Areas to the north and higher elevations for these groups of species are either bounded by the Chukchi, or Beaufort Seas, or are reduced in area for the montane species. The interior species associations tend to be dominated by species found on warmer and drier microsites and thus we expect that habitat suitability for this group of species will generally increase under future scenarios at least in the eastern interior.

In an attempt to evaluate the potential vulnerabilities of rare plant species in Alaska to climate change, we modeled the distribution of current and future climatic envelopes of 34 rare plant species. Specifically we address if predicted suitable habitat contracts in area and if the region of predicted suitability is different in 50 years. We anticipated that montane-associated species and species endemic to the Arctic Coastal Plain would be more vulnerable than species of other biogeographic affinities to climate change. Last, we examined the importance of temperature relative to other climate and geographic variables in the development of distribution models for these species.

METHODS

We modeled the current and future ecological niches using presence data for seven to ten species from each of four biogeographic regions in Alaska: Arctic Coastal Plain, interior, montane (primarily Alaska and Brooks Ranges), and a combined Aleutian and southeastern coastal region (Aleutian-south coastal, table 1). Aleutian and southeastern coast regions were combined because they share biogeographic affinities (fig. 1) and the small numbers of populations and incomplete data layers in the western Aleutians hampered our ability to treat that region independently. We included species considered rare to imperiled in the state for which there were approximately ten or more occurrences.

Population locations were obtained from the Alaska Natural Heritage Program's rare plant database (AKNHP 2012). The majority of these records are based on georeferenced vouchered specimens housed in herbaria such as the University of Alaska Museum and the University of Alaska Anchorage, as well as from the USDA Forest Service NRIS database. Species occurrences that were less than 1 km apart were eliminated from the analysis.

The predictor variables we used included current and projected climate data created for Alaska by the Scenarios Network for Alaska Planning (SNAP 2010, 1 km^2 grid cells). The future climate projection is based on the downscaled output from five of the International Panel on Climate Change's Global Circulation models. We used the climate projection for 2060 under the intermediate (A1B) emission scenarios. Climate variables used to develop the models included mean annual temperature, mean annual precipitation, and growing season length (number of frost-free days). Additionally, we included slope and elevation, which were extracted from the National Elevation Dataset for Alaska (Gesch 2007 and Gesch et al. 2002; approximately 60 meter resolution).

We used the maximum entropy modeling program MaxEnt version 3.3.1 (Phillips et al. 2006, Phillips and Dudik 2008) to produce the species distribution models. MaxEnt calculates expected levels of species presence using presence-only data, and has been shown to outperform more established modeling methods, such as GARP and BIOCLIM (Elith et al. 2006). When the number of data points available made it possible, runs were cross-validated. Occurrences were randomly split into a number of groups, and models were created omitting each group of occurrences in turn. Models run from previously omitted occurrences are then used for evaluation. We used area under the curve (AUC) statistics derived from receiver operating characteristics (ROC) analyses, which is automatically calculated by Maxent, to estimate model performance. AUC values range between 0.5 and 1, with values between 0.5 - 0.7 being relatively poor, those between 0.7 and 0.9 being useful, and those above 0.9 indicating relative high accuracy (Swets 1988). Finally, our knowledge of individual species and their habitat preferences was also incorporated to make final determinations on which models were useful and which ones were not as reliable.

We developed an index to compare the relative importance of the five predictor variables in determining suitability for the biogeographic groups of species. Percent variable contributions are generated from MaxEnt and we used the first two variables that contributed most to the model for each species were given scores of 1.0 or 0.5, for first and second variable contribution, respectively. The ratio of scores for each variable to the total for all species in the biogeographic group was then calculated. Thus the variable most important to the majority of species in the group received a higher score. We compared changes in predicted suitability over the 50 year time-step by visually comparing the mapped outputs.

RESULTS

In general, model performance was correlated with the number of occurrences used to develop the model. Species with greater than 15 known occurrences, and for which we could run cross-validation statistics with 5-10 replicates performed the best. Predicted habitat suitability models for 2010 and 2060 are shown in figure 2 for three species within each biogeographic group to demonstrate the range of responses.

Overall, species had varied responses to future climates, with predicted suitabilities increasing in some cases and decreasing in others. However, there were some consistent patterns within biogeographic groups. Consistent with expectations, all Arctic Coastal Plain species exhibited a decrease in suitable habitat as a result of climate change (albeit with poor model performance). Model results from the Aleutian-south coastal and montane biogeographic groups suggest that the area of suitable habitat shifts north as expected, but that the area of suitable habitat is roughly similar or increases under these future climate projections. Last, model results suggest a range of vulnerabilities of interior species under future climate predictions.

Arctic Coastal Plain Species

Model performance for most of the Arctic Coastal Plain species was poor. Many of the rare species we selected from this region have few known occurrences (3-20 per species), and even when cross-validated the model outputs were still either over-fitted (too constrained to the predictor variables and lack generality) or potentially lacking a variable that would have served as a stronger predictor. There was however a consistent trend among all arctic species analyzed: the area of suitable habitat shifted northward and declined in the 2060 models (fig. 2). The model obtained for the arctic grass ***Koeleria asiatica*** Domin, which is considered rare in the state and of long-term conservation concern globally, was well-supported (22 known locations, ten replicates, AUC 0.976). Predicted habitat for this species shows a general reduction in the area and degree of suitability by 2060, with particular reductions in the southern and western portions of its current range. We also retained the modeled outputs for ***Papaver gorodkovii*** Tolm. & Petrovsky (13 known locations, three replicates, AUC 0.964) and for ***Cardamine microphylla*** M.F. Adams (nine known locations, three replicates, AUC 0.919). Model runs for ***Draba subcapitata*** Simmons, ***Ranunculus sabinei*** R.Br., and ***Symphyotrichum falcatum*** ssp***. falcatum*** (Lindl.) G.L. Nesom, which are all imperiled and restricted to the Arctic, could not be replicated due to the lack of distinct occurrences (three to six). Models for these species were highly over-fitted and discarded after an initial run. Although our confidence in the models for ***Mertensia drummondii*** (Lehm.) G. Don***,*** ***Pleuropogon sabinei*** R.Br.***, Draba pauciflora*** R.Br.***, Symphyotrichum pygmaeum*** Brouillet & Sugirthini***, Saxifraga rivularis*** ssp***. arctolitoralis*** (Jurtzev & V.V. Petrovsky) M.H. Jørg. & Elven, and ***Poa hartzii*** ssp***.***

alaskana Soreng**.** was low, all of these species displayed similar constrictions of predicted suitable habitat. In many cases the declines were dramatic, for example no suitable habitat was identified for ***Mertensia drummondii*** under this scenario by 2060. Species models in this biogeographic group were driven primarily by mean annual temperature, followed by elevation and the other variables (fig. 3).

Montane Species

Unlike the Arctic Coastal Plain species, montane species all had more than 15 occurrences (most had more than 40 known presences), and models were consequently run with cross-validation (ten or sometimes three replicates per species). High AUC values (0.83 to 0.93) and the omission versus commission analyses indicated strong model performance across all species in this group.

The overall trend for the montane species is that the distribution of predicted suitable habitat remains similar in extent or even increases within the next 50 years (fig. 2). In particular, for many of the montane species, increased habitat suitability is evident in the Brooks Range, while little reduction on the southern edge of their distribution is indicated. However, some reductions of current habitat suitability were evident in the model for ***Aphragmus eschscholtzianus*** Andrz. ex DC. in the southwestern portion of its range on the Alaska Peninsula. Montane species models were primarily driven by elevation and precipitation.

Aleutian-South Coastal Species

Models for Aleutian-south coastal species with greater than 15 occurrences were also reliable. However, ***Oxygraphis glacialis*** (Fisch.) Bunge and ***Plagiobothrys orientalis*** (L.) I.M. Johnst. were discarded because of poor model performance and over-fitting. Many of the Aleutian-coastal species models indicated increased future habitat suitability in the Bristol Bay region to the north of their current locations and some moderate decline in suitability in southeastern Alaska. Only modest declines in suitabilities in their current ranges in southwestern Alaska were indicated (fig. 2). It should be stressed that most of the species in this biogeographic group are associated with strongly maritime-influenced habitats and therefore, the increased suitabilities in the highlands of southwestern Alaska projected by many models are unlikely to be reflective of truly suitable habitat. Aleutian-south coastal species models were driven primarily by mean annual precipitation (fig. 3).

Interior Species

Interior species displayed the most diverse response to climate change. ***Lupinus kuschei*** Eastw. and ***Physaria caldera*** (G.A. Mulligan & A.E. Porsild) O'Kane & Al-Shehbaz were discarded for poor model performance. Some species showed large declines in the area of predicted suitable habitat by 2060 (e.g., ***Campanula aurita*** Greene**,** ***Cerastium maximum*** L.**,** ***Draba murrayi*** G.A. Mulligan**,** ***Erysimum asperum*** var. ***angustatum*** (Rydb.) B. Boivin**,** ***Eriogonum flavum*** var. ***aquilinum*** Reveal**,** ***Alyssum obovatum*** (C.A. Mey.) Turcz.**,** ***Antennaria densifolia*** A.E. Porsild; fig. 2). However, in almost all cases, predicted habitat suitability in 2060 remained high in the specific areas where populations are currently known. In addition, other taxa exhibited an increase and/or shift in their predicted suitable habitat (e.g. ***Artemisia tanacetifolia*** L. and ***Corispermum ochotense*** Ignatov; fig. 2). Precipitation was the most important variable driving the species models for the interior species model, while slope and the other variables were important predictors for a minority of species (fig. 3).

DISCUSSION

While the rare flora of Alaska is less threatened by anthropogenic factors than floras to the south, our modeling results suggest that some groups of species may have difficulties tracking suitable habitats and are vulnerable to climate change. In particular, models of the Arctic Coastal Plain endemics suggest a common pattern of dramatic decrease in the area of predicted suitable habitat. Although we restricted our analysis to Alaska, areas of future suitable climate for many of these species would be expected to occur in higher latitude polar regions, such as in the Canadian Archipelago. Migration corridors to these areas, however, would require long distance dispersal across the water or sea ice. Population genetic data from a number of arctic plant species does suggest high dispersal ability (Abbott and Brochmann 2003). Interestingly, modeling of the arctic tundra biome more broadly has suggested that this system may be less vulnerable to shifts than many other biomes, as shifts in other biomes are often sensitive to relatively small changes in temperature and precipitation (Murphy et al. 2010, Loarie et al. 2011). The arctic tundra habitat on the Seward Peninsula, which is much nearer to the margin of the arctic tundra biome climate envelope than the Arctic Coastal Plain, is anticipated to diminish dramatically in this time frame (Murphy et al. 2010). Therefore the Bering Strait associated rare species (which were not modeled here) could be at particular risk. While biological organization may not change dramatically at broader physiognomic levels (i.e., treeless tundra persists) on the Arctic Coastal Plain, the composition of communities within the biomes may change due to individual species responses. In particular, models of these rare species suggest that changes in their climate envelopes could be striking.

Rare species associated with the Aleutian-south coastal and montane regions appear more secure than the species of the Arctic Coastal Plain and interior regions. These species are found in the southern and central portion of the state and in areas with high topographic complexity. Thus future suitable climate envelopes are generally proximal to current climate envelopes. In regions to the south, alpine habitats and associated species have been recognized as sky islands that are particularly vulnerable to climate change (e.g., Kupfer et al. 2005, Gifford and Kozak 2012). In Alaska, the reduction in alpine habitats in response to climate change is likely substantially less than regions to the south since alpine habitats occur at much lower elevations and a relatively large area still remains at higher elevations. Future suitable habitat generally increased in the Brooks Range for the montane associates and for many species that are currently associated with the Alaska and Coastal Ranges there is no clear high elevation north-south dispersal route to the Brooks Range. Also, even though suitable habitat was predicted to remain similar in extent or increase for Aleutian-south coastal and montane-associated species, reductions in suitabilities at the southern margin of the ranges of some species were implied; thus local population decline at the edge of some species' ranges is a concern. Therefore, some caution should be taken in assuming with increasing area of suitable habitat modeled there is reduced threat. Due to lack of some adequate environmental data layers and few known locations, we did not model suitable habitats for the rarest Aleutian Island endemics. These species would likely face significant dispersal barriers assuming suitable climates shift from current locations. However, the only USFWS Listed plant taxon in the state is the Aleutian shield fern (***Polystichum aleuticum***) and of all vascular plant groups, ferns are generally not dispersal limited (Tryon 1966, 1970, Perrie et al. 2010).

Mean annual precipitation, rather than temperature, was the predictor variable that explained the most variation in suitable habitat across species models. The degree of uncertainty in patterns of future precipitation in general is quite high however, and thus constrains the confidence in models of future suitable habitat in cases where precipitation an important predictor variable (Lawler 2012). Second, plants are expected to respond to soil moisture rather than precipitation ***per se***, and soil moisture is a more complex variable involving temperature, evapotranspiration, etc. Despite these caveats, many of the rare species, particularly in interior Alaska, are clearly associated with unusually dry microsites (see Lipkin and Murray 1997) and therefore changes in precipitation (and temperature) would be expected to have large impacts on the size and distribution of suitable habitat. Even small decreases in precipitation and increases in temperature are expected to result in potentially large areas of conversion of forest habitats to open, steppe-bluff habitats (Lloyd et al. 2011), which could result in a greater area of suitable habitat for this group of rare species.

The lack of importance of temperature in explaining variation in the models is noteworthy. It is quite possible that many of these species occur in areas with relatively large variation in mean annual temperature and although they occur in a relatively narrow geographic region, it encompasses a range of elevations, aspects, and distances to coast. Thus variation in mean annual temperatures associated with known locations would be expected to be high and therefore have reduced predictive ability relative to other variables. Second, since we have only treated temperature in a very coarse manner (mean annual temperature) we are unlikely to capture many important climate niche parameters. For example, individual plant species would be expected to respond to finer-scale aspects of temperature, such as minimum winter temperatures or maximum summer temperatures, variables that may be only weakly correlated with mean annual temperature.

These model outputs are intended as a hypothesis generating exercise and should be viewed with caution and an awareness of their limitations (see Davis et al. 1998). First, we have no ***a priori*** information that the habitat of the species modeled is in fact related to the climate and topographic variables used. While mean annual temperature and precipitation are accepted in general to be the most important niche parameters for vascular plants (see Woodward 1987, Davis and Shaw 2001, Hughes 2000, McCarty 2001, Walther et al. 2002), it is possible that these variables are not important within the scope of the geographic region investigated. Populations of these rare plants may be more constrained by finer-scale variables. For example, soil moisture-holding capacity has been shown to be a major determinant of the distribution of three alpine tundra willow species (Dawson 1990) and the presence of mycorrhizal symbionts has been shown to be a major component determining species' distributions (McCormick et al. 2012). Second, with few known locations for many of the rarest species, there is greater uncertainty about the relationship of the species with the predictor variables, leading to poor or over-fitted models. Third, we have little ability to infer if the pattern of current and future suitable habitats of the most critically imperiled taxa (that were not modeled because of low sample size) would be similar to the model outputs associated with the species with more occurrences. Thus we restrict comments on climate vulnerabilities of our rarest species. Finally, the majority of rare plants in Alaska are associated with uncommon substrates (e.g., sand dunes, limestone outcrops, wet scree, etc.) and we were not able to include these as predictor variables because high resolution spatial data is not avaialable for the state. Thus the habitat suitability outputs produced in these models represent a coarse perspective based on a limited number of predictors with at least one of the major predictors (substrate type) omitted. Last, it should be emphasized that we are unaware of indirect impacts of climate change on rare plants. Changes in disturbance regimes and antagonistic and mutualistic interactions, herbivory, pathogens, etc. are likely to have equal or greater impacts on rare plant species than direct effects of climate (Davis et al. 1998, Klanderude 2005, Suttle et al. 2007, Adler et al. 2009).

This study does, however, provide a direction for future research on the impact of climate change on Alaska's rare plants. These initial findings suggest that natural resource managers in the state should give greater priority to inventorying, monitoring, and conducting experimental work on rare vascular plants in the Arctic. Even though these species are not currently listed as threatened or endangered, the lack of information we have on these plants severely limits our ability to understand their current rarity as well as predict how future changes in the state will affect them. Currently we have almost no information on baseline population trends or habitat changes of rare species in the state and monitoring efforts would be invaluable in gauging if populations of the identified vulnerable species are in fact showing signs of change. Second, we see a great value in studies to test the relationship of direct and indirect effects of climate on niche space by relating population vital rates to environmental parameters in natural populations or in newly established populations subjected to current and predicted future climates (McLean and Aitken 2012). Future modeling studies will include rare species from the Bering Strait and strictly southeastern maritime ecoregions, as well as including the westernmost Aleutian species, and by including more widespread arctic and Aleutian species.

ACKNOWLEDGMENTS

Dave Yokel with the Alaska Northern Region of the Bureau of Land Management and Michael Shephard and Amy Miller with the Southwest Alaska Network, National Park Service supported previous modeling efforts, integral in this study. Timm Nowacki, Erin Johnson, and Nancy Norvell with the Alaska Natural Heritage Program, University of Alaska Anchorage assisted in the modeling efforts. Amy Miller, Tracey Gotthardt, and Miles Spathelf offered valuable insights and edits on earlier versions of this manuscript.

LITERATURE CITED

Abbott, R.J; Brochmann, C. 2003. History and evolution of the arctic flora: In the footsteps of Eric Hultén. Molecular Ecology 12: 299-313.

Adler, P.B.; Leiker, J.; Levine, J.M. 2009. Direct and indirect effects of climate change on a prairie plant community. PLoS ONE 4(9): e6887. doi:10.1371/journal.pone.0006887.

ACIA. 2005. Arctic Climate Impact Assessment: Impacts of a warming climate. University of Cambridge Press, Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo.

AKNHP. 2012. Rare vascular plants of Alaska. Alaska Natural Heritage Program, University of Alaska Anchorage. http://aknhp.uaa.alaska.edu/botany/rare-plants-species-lists/2012-rare-vascular-plant-list. 10 March 2012.

Chapin, F.S.III; Trainor, S.F.; Huntington, O.; Lovecraft, A.L.; Zavaleta, E.; Natcher, D.C.; McGuire, A.D.; Nelson, J.A.; Ray, L. Calef, M.; Fresco, N.; Huntington, H.; Rupp, T.S.; DeWilde, L.; Naylor, R.L. 2008. Increasing wildfire in Alaska's boreal forest: pathways to potential solutions of a wicked problem. Bioscience 58:531-540.

Carlson, M.L.; Cortés-Burns, H.; Miller, A. 2007. Areas of plant radiation and migration in Alaska: Testing Hultén's ideas of elemental areas and rare plant diversity in Alaska. AAAS, Arctic Chapter Annual Meeting 24-26 September 2007, Anchorage.

Carlson, M.L.; Shephard, M. 2007. Is the spread of non-native plants in Alaska accelerating? In: Meeting the challenge: invasive plants in Pacific Northwest ecosystems, Portland, OR. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, En. Tech. Rep. PNW-GTR-694: 111-127.
Cortés-Burns, H.; Carlson, M.L.; Lipkin, R.; Flagstad, L.; Yokel, D. 2009. Rare vascular plants of the North Slope: a review of the taxonomy, distribution, and ecology of 31 rare plant taxa that occur in Alaska's North Slope región. BLM Alaska Technical Report 58. BLM/AK/GI-10/002+6518+F030. pp. 116.

Davis, A.J.; Jenkinson, L.S.; Lawton J.H.; Shorrocks, B.; Wood, S. 1998. Making mistakes when predicting shifts in species range in response to global warming. Nature 391: 783–786.

Davis, M.B. & Shaw, R.G. 2001. Range shifts and adaptive responses to Quaternary climate change. Science, 292, 673–679.

Dawson, T.E. 1990. Spatial and physiological overlap of three co-occurring alpine willows. Functional Ecology, 4, 13-25.

Dial, R.J.; Berg, E.E.; Timm, K.; McMahon, A.; Geck, J. 2007. Changes in the alpine forest-tundra ecotone commensurate with recent warming in southcentral Alaska: Evidence from orthophotos and field plots. Journal of Geophysial Research 112: G04015, doi:10.1029/2007JG000453.

Elith, J.; Kearney, M.; Phillips, S. 2010. The art of modelling range-shifting species. Methods in Ecology and Evolution 1:330-342.

Fielding, A.H.; Bell, J.F. 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environmental Conservation 24:38-49.

Gesch, D.B. 2007. The National Elevation Dataset, in Maune, D., ed., Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd Edition: Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing, p. 99-118.

Gesch, D.; Oimoen, M.; Greenlee, S.; Nelson, C.; Steuck, M.; Tyler, D. 2002. The National Elevation Dataset: Photogrammetric Engineering and Remote Sensing 68: 5-11.

Gifford, M.E.; Kozak, K.H. 2012. Islands in the sky or squeezed at the top? Ecological causes of elevational range limits in montane salamanders. Ecography 35: 193-203.

Grundt, H.H.; Kjølner, S.; Borgen, L.; Rieseberg, L.H.; Brochmann, C. 2006. High biological species diversity in the arctic flora. Proceedings of the National Academy of Sciences 103: 972–975.

Hughes, L. 2000. Biological consequences of global warming: is the signal already apparent? Trends in Ecology and Evolution, 15, 56–61.

Hultén, E. 1968. Flora of Alaska and Neighboring Territories. Stanford University Press, Stanford, California.

IPCC 2007. Climate change 2007: impacts, adaptationand vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Klanderud, K. 2005. Climate change effects on species interactions in an alpine plant community. J Ecology 93: 127–137.

Klein, D.; Berg, E.E.; Dial, R. 2005. Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska. Canadian Journal of Forestry Research 35: 1931–1941.

Kupfer, J.A.; Balmat, J.; Smith, J.L. 2005. Shifts in the potential distribution of sky island plant communities in response to climate change. USDA Forest Service Proceedings RMRS-P-36.

Lawler, J. 2012. Anticipating the impacts of climate change on native plants: models, forecasts, and implications. Conserving Plant Biodiversity in a Changing World: A View from NW North America. Seattle, Washington. 14 March 2012.

Lipkin, R.; Murray, D.F. 1997. Alaska rare plant field guide. U.S. Fish and Wildlife Service, National Park Service, Bureau of Land Management, Alaska Natural Heritage Program, and U.S. Forest Service.

Lloyd, A.H.; Duffy, P.; Mann, D.H.; Leonawicz, M.; Blumstein, M.; Pendall, E. 2011. Threshold Responses of Aspen and Spruce Growth to Temperature May Presage a Regime Shift in the Boreal Forest. American Geophysical Union, Fall Meeting 2011, abstract #U51C-05.

Loarie, S.R.; Duffy, P.B.; Hamilton, H.; Asner, G.P.; Field, C.B.; Ackerly, D.D. 2011. The velocity of climate change. Nature 462:1052-1056.

McCarty, J.P. 2001. Ecological consequences of recent climate change. Conservation Biology, 15, 320–331.

McCormick, M.K.; Taylor, D.E.; Juhaszova, K.; Burnett, R.K. Jr; Whigham, D.F.; O'Neill, JP. 2012. Limitations on orchid recruitment: not a simple picture. Molecular Ecology. doi: 10.1111/j.1365-294X.2012.05468.x

McLane, S.C.; Aitken, S.N. 2012. Whitebark pine (*Pinus albicaulis*) assisted migration potential: testing establishment north of the species range. Ecological Applications Vol??:142-153.

Meffe, G.K.; Carroll, C.R. 1997. Principles of Conservation Biology. Sinauer Associates, Inc., Sunderland, Massachusetts.

Murphy, K.; Huettmann, F.; Fresco, N.; Morton, J. 2010. Connecting Alaska landscapes into the future. Final Report. Scenarios Network for Alaska Planning, University of Alaska, Fairbanks, Alaska.

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

Perrie, L.R.: Ohlsen, D.J.; Shepherd, L.D.; Garrett, M.; Brownsey, P.J., Bayly, M.J. 2010. Tasmanian and Victorian populations of the fern *Asplenium hookerianum* result from independent dispersal from New Zealand. Australian Systematic Botany 23: 387–392.

Phillips, S.J.; Anderson, R.P.; Schapire, R.E. 2006. Maximum entropy modeling of species geographic distributions. Ecological Modelling 190:231-259.

Phillips, S.J.; Dudik, M. 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. Ecography 31:161-175.

Roland, C. 2012. Modeling the diversity of rare and endemic plants at the landscape scale in Denali National Park: implications of climate change for this unique natural heritage. Conserving Plant Biodiversity in a Changing World: A View from NW North America. Seattle, Washington. 14 March 2012.

Serreze, M.C.; Walsh, J.E.; Chapin, F.S. III; Osterkamp, T; Dyurgerov, M.; Romanovsky, V.; Oechel, W.C.; Morison, J.; Zhang, T.; Barry, R.G. 2000. Observational evidence of recent change in the northern high-latitude environment. Climate Change 46:159-207.

SNAP. 2010. Scenarios Network for Alaska Planning (http://www.snap.uaf.edu/gis-maps) Alaska Climate Datasets. University of Alaska Fairbanks, Fairbanks, Alaska

Soja, A.J.; Tchebakova, N.M.; French, N.H.F.; Flannigan, M.D.; Shugart, H.H.; Stocks, B.J.; Sukhinin, A.I.; Parfenova, E.I., Chapin, F.S.III; Stackhouse, P.W.Jr. 2006. Climate-induced boreal forest change: predictions versus current observations. Global and Planetary Change 56: 274–296.

Suttle, K.; Thomsen, M.; Power, M. 2007. Species interactions reverse grassland responses to changing climate. Science 315: 640–642.

Swets, J.A. 1988. Measuring the accuracy of diagnostic systems. Science 240:1285-1293.

Tape, K.; Sturm, M.; Racine, C. 2006. The evidence for shrub expansion in Northern Alaska and the Pan-Arctic. Global Change Biology 12:686-702.

Tryon, A.F. 1966. Origin of the fern flora of Tristan de Cunha. British Fern Gazette 9: 269–276.

Tryon, R.M. 1970. Development and evolution of fern floras of oceanic islands. Biotropica 2: 76–84.

USDA, Economic Research Service. 2012. State Fact Sheets. http://www.ers.usda.gov/StateFacts/. (12 June 2012).

USFWS Federal Registry. 1988. http://alaska.fws.gov/fisheries/fieldoffice/anchorage/endangered/pdf/factsheet_alsf.pdf. (9 June 2012).

Walther, G.R., Post, E., Convey, P., Menze, 1, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O. & Bairlein, F. 2002. Ecological responses to recent climate change. Nature, 416, 389–395.

Wendler, G.; Shulski, M. 2009. A century of climate change for Fairbanks, Alaska. Arctic 62: 295-300.

Wilcove, D.S.; Master, L. L. 2008. How Many Endangered Species are there in the United States? Frontiers in Ecology and the Environment 3: 414-420.

WNHP. 2012. List of Vascular Plants Tracked by the Washington Natural Heritage Program. http://www1.dnr.wa.gov/nhp/refdesk/lists/plantrnk.html. (10 March 2012).

Woodward, F.I. 1987. Climate and plant distribution. Cambridge University Press, Cambridge.

Table 1. Species used in the habitat modeling, biogeographic association, NatureServe global and current Alaska Natural Heritage Program state rarity ranks, and number of occurrences in Alaska. The Aleutian-south coastal association is abbreviated 'Aleutian-coastal' and the Arctic Coastal Plain is abbreviated 'Arctic'.

Species	Region	Global Rank	State Rank	Number of occurrences
Alyssum obovatum	Interior	G5	S2S3	12
Antennaria densifolia	Interior	G3	S2	9
Aphragmus eschscholtzianus	Montane	G3	S4	57
Arnica ovata	Montane	G5	S2S3Q	18
Artemisia tanacetifolia	Interior	GNR	S3	26
Atriplex gmelinii var. *alaskensis*	Aleutian-coastal	G3G4Q	S4	27
Campanula aurita	Interior	G4	S4	42
Cardamine microphylla	Arctic	G3G4	S2	9
Cerastium maximum	Interior	G4	S4	26
Corispermum ochotense	Interior	G3G4	S3	14
Douglasia alaskana	Aleutian-coastal	G3	S4	45
Draba macounii	Montane	G3G4	S3	21
Draba murrayi	Interior	G2	S2S3	22
Draba pauciflora	Arctic	G4	S2	9
Erigeron porsildii	Montane	G3G4	S3S4	21
Eriogonum flavum var. *aquilinum*	Interior	G5T2	S2	18
Erysimum asperum var. *angustatum*	Interior	G5T1	S2	19
Koeleria asiatica	Arctic	G4	S3	22
Lupinus kuschei	Interior	G3G4	S2	16
Mertensia drummondii	Arctic	G2G3	S2	16
Noccaea arctica	Montane	G3	S4	48
Oxygraphis glacialis	Aleutian-coastal	G4G5	S3	16
Papaver alboroseum	Montane	G3G4	S4	46
Papaver gorodkovii	Arctic	G3	S2S3	13
Physaria calderi	Interior	G3G4	S2	10
Plagiobothrys orientalis	Aleutian-coastal	G3G4	S3	11
Pleuropogon sabinei	Arctic	G4G5	S1	11
Poa hartzii spp. alaskana	Arctic	G3G4T1T2	S1S2	8
Ranunculus pacificus	Aleutian-coastal	G3	S3S4	25
Romanzoffia unalaschensis	Aleutian-coastal	G3	S3S4	39
Rumex beringensis	Aleutian-coastal	G3	S3	23
Salix setchelliana	Montane	G4	S4	50
Saxifraga rivularis ssp. *arctolitoralis*	Arctic	G5T2T3	S2	9
Symphyotrichum pygmaeum	Arctic	G2G4	S2	9

Figure 1. Hierarchical cluster analysis of 76 rare plant taxa occurring in more than one 1:250,000 mi^2 grid cells and ecoregions (Nowacki et al. 2001). Biogeographic groupings are indicated to the right of the boxes.

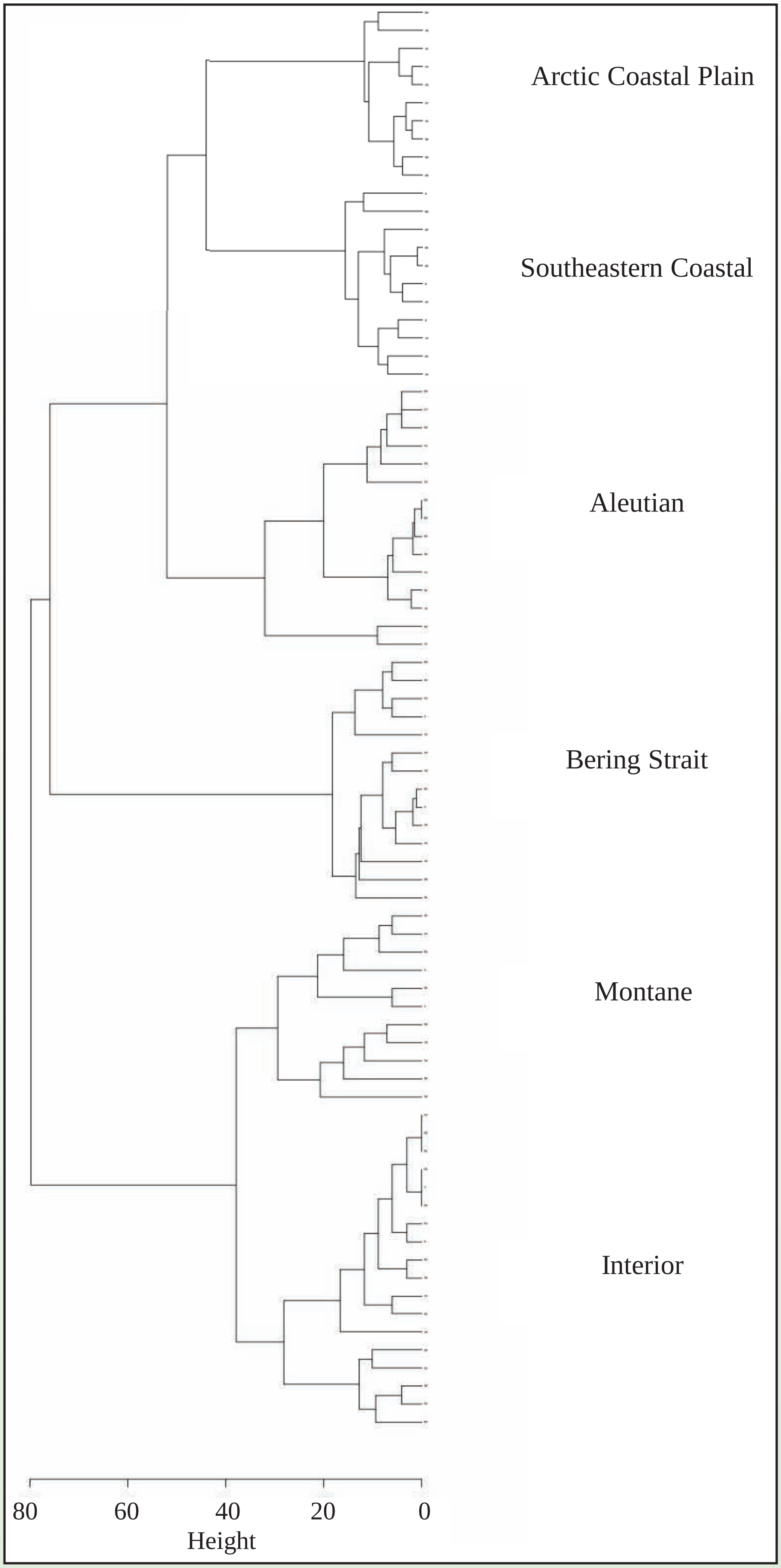
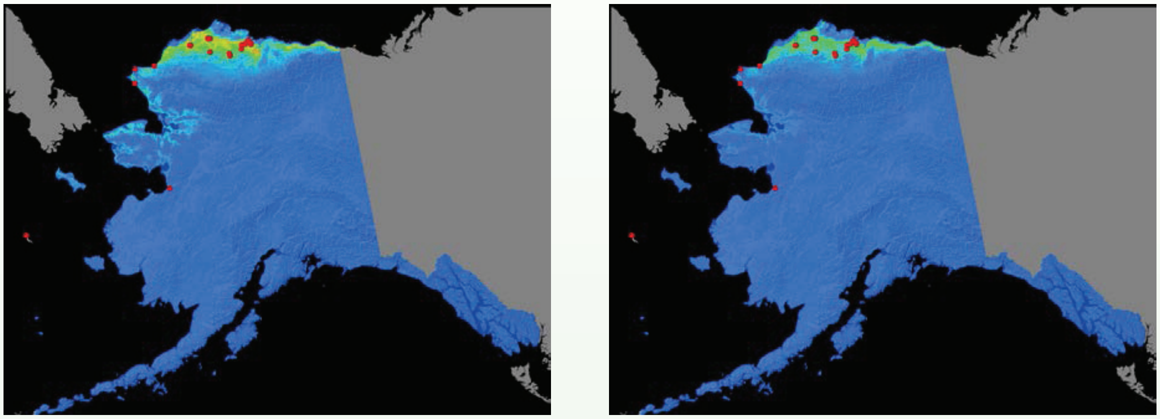
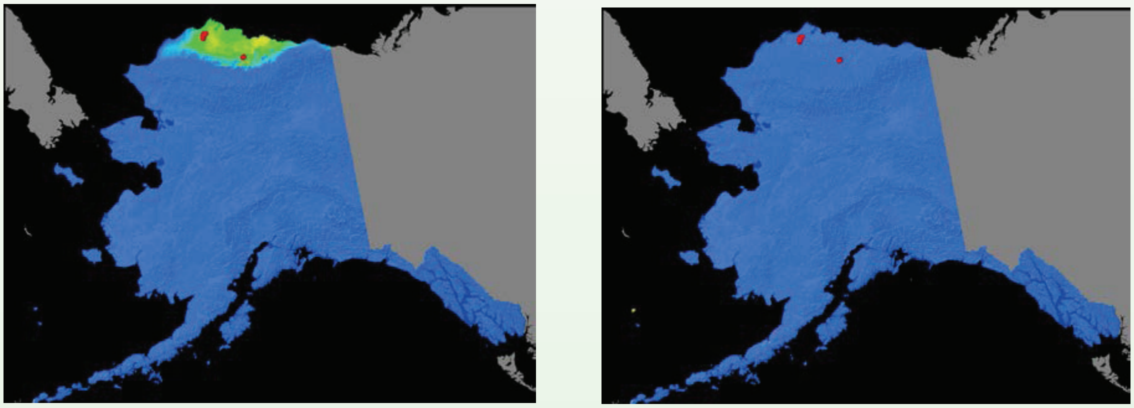


Figure 2. Current and future species habitat suitability for four biogeographic groups of rare species in Alaska (warm colors are used for pixels with potentially suitable habitat while cool colors indicate pixels or areas where the species is less likely to occur; the spectrum ranges from red to blue). Known occurrences are indicated as red dots.

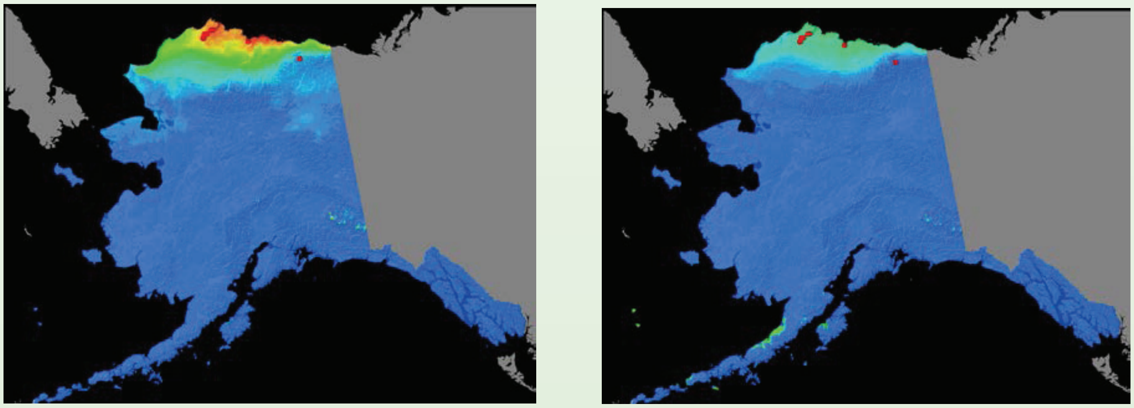
Arctic Coastal Plain species distributions



Present (2010) and future (2060) ecological niche models for *Koeleria asiatica*.

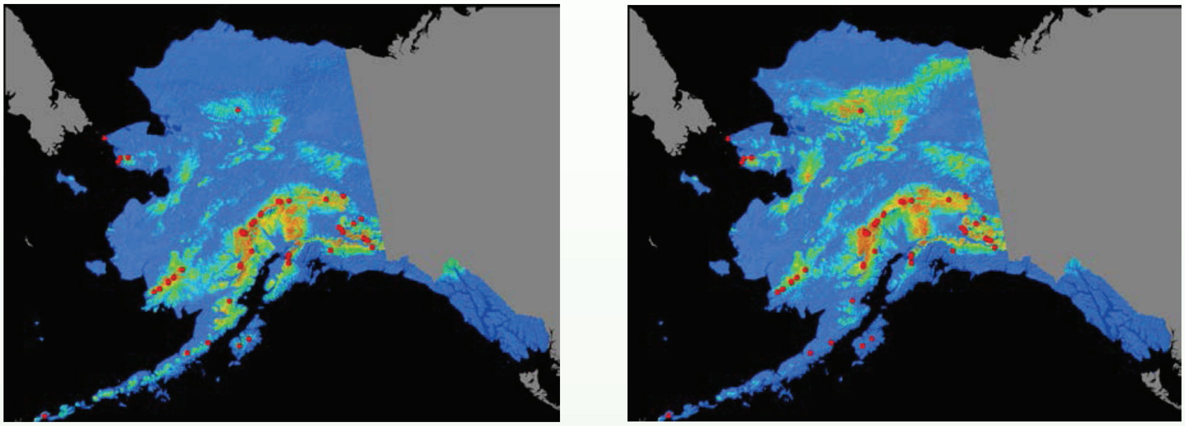


Present (2010) and future (2060) ecological niche models for *Mertensia drummondii*.

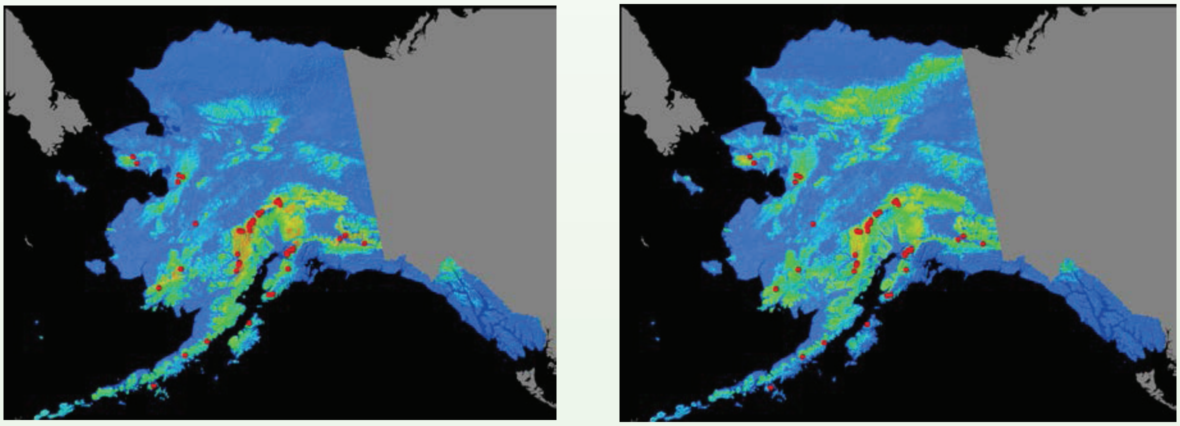


Present (2010) and future (2060) ecological niche models for *Poa hartzii* ssp. *alaskana*.

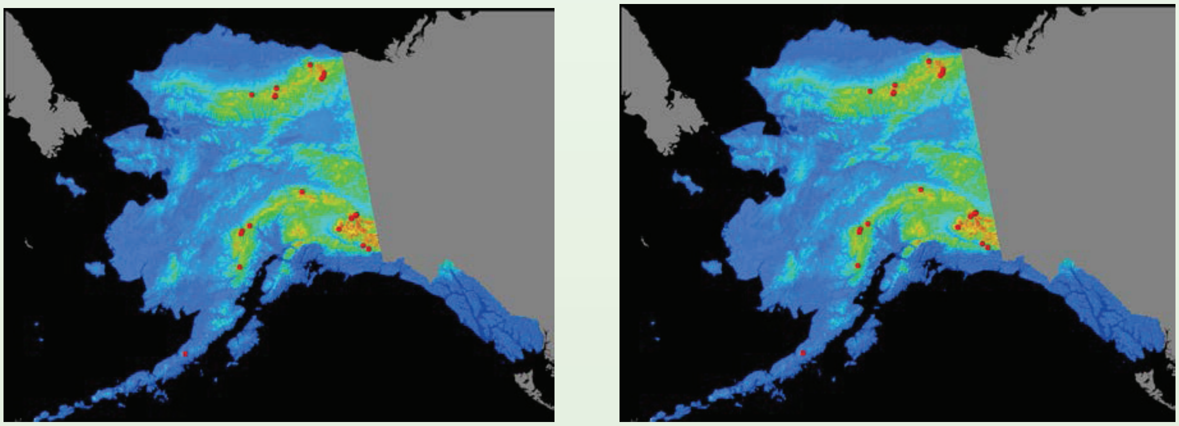
Montane species distributions



Present (2010) and future (2060) ecological niche models for *Aphragmus eschscholtzianus*.

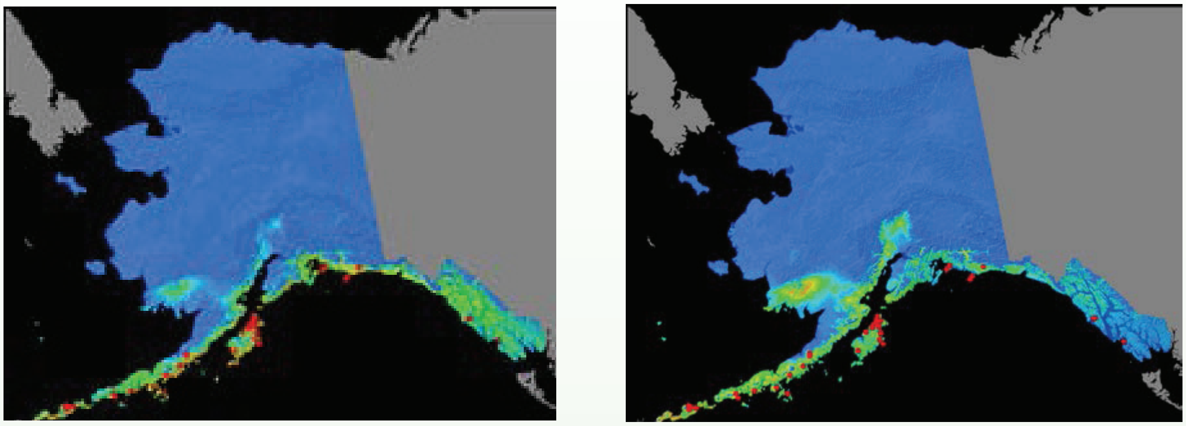


Present (2010) and future (2060) ecological niche models for *Douglasia alaskana*.

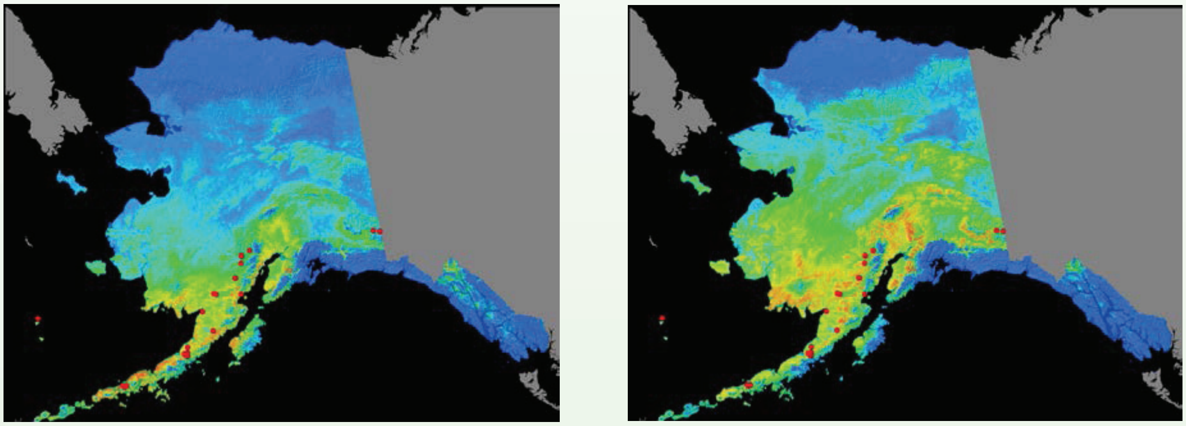


Present (2010) and future (2060) ecological niche models for *Draba macounii*.

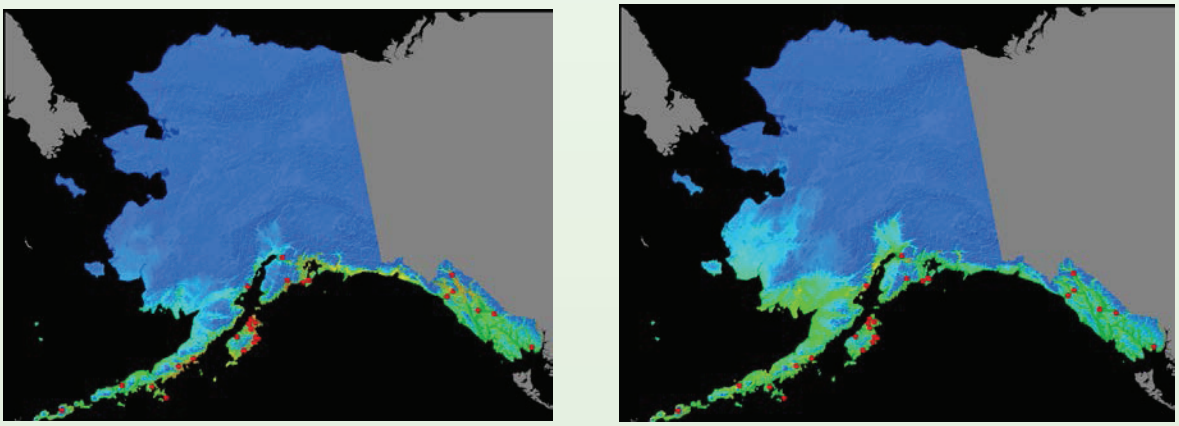
Aleutian-south coastal species distributions



Present (2010) and future (2060) ecological niche models for *Romanzoffia unalaschcensis*.

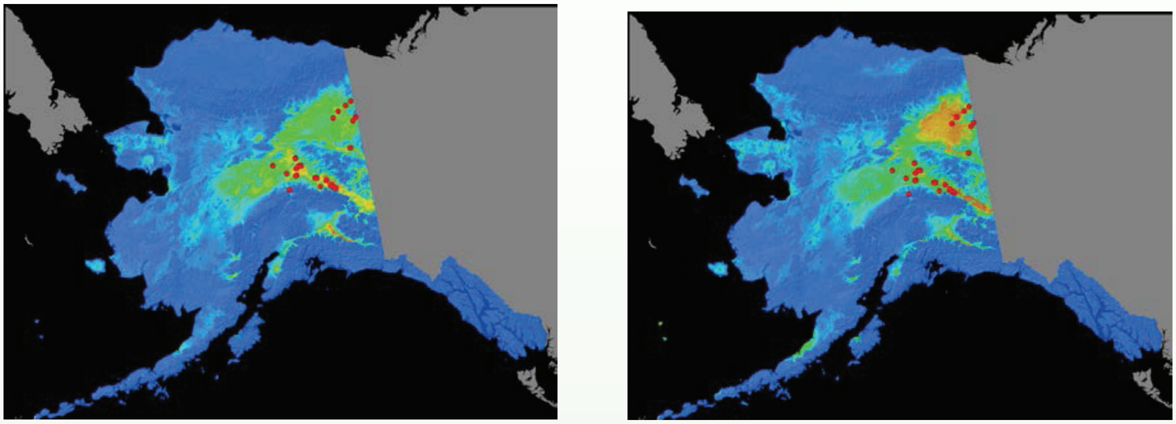


Present (2010) and future (2060) ecological niche models for *Rumex beringensis*.

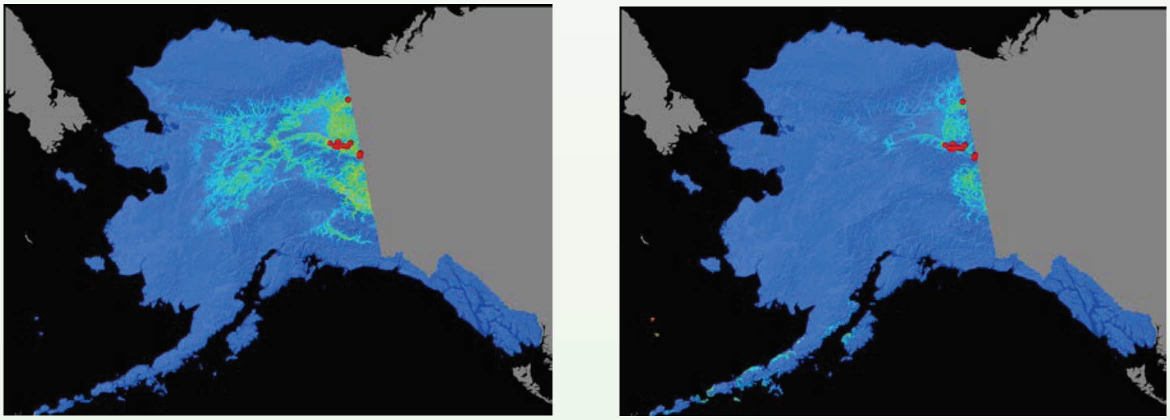


Present (2010) and future (2060) ecological niche models for *Atriplex gmelinii*.

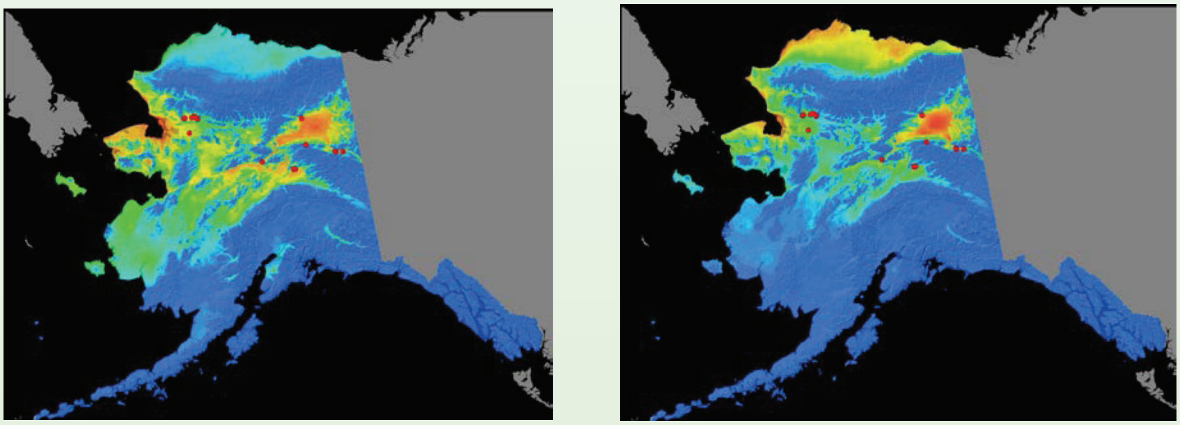
Interior species distributions



Present (2010) and future (2060) ecological niche models for *Artemisia tanacetifolia*.



Present (2010) and future (2060) ecological niche models for *Erysimum asperum* var. *angustatum*.



Present (2010) and future (2060) ecological niche models for *Corispermum ochotense*.

Figure 3. Index of predictor variable contributions to species distribution models for four biogeographic groups. The Aleutian-south coastal association is abbreviated 'Aleutian-coastal' and the Arctic Coastal Plain is abbreviated 'Arctic'.