FINAL REPORT

Climate-Change Vulnerability in the Pacific Northwest: A Comparison of Three Approaches

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Public Summary

Climate change is already affecting species in many ways. Because individual species respond to climate change differently, some will be adversely affected by climate change whereas others may benefit. Successfully managing species in a changing climate will require an understanding of which species will be most and least impacted by climate change. Although several approaches have been proposed for assessing the vulnerability of species to climate change, it is unclear whether these approaches are likely to produce similar results. In this study, we compared the relative vulnerabilities to climate change of 76 species of birds, mammals, amphibians, and trees based on three different approaches to assessing vulnerability. We compared 1) projected shifts in species distributions to 2) an assessment based on expert opinion and projected changes in climate to 3) an approach based on the current and future climatic conditions within species' current ranges. We found that the three approaches provided substantially different rankings of the species. Some species were determined to be highly vulnerable by one approach but only moderately vulnerable by the other two approaches. Only one species, the caribou, was consistently ranked in the top ten most vulnerable species by all three approaches. This is not entirely surprising given that the three measures assess different aspects of vulnerability and are based on different types of information. Nonetheless, these results are important because they indicate that more than one approach may be needed to adequately assess vulnerability—and that basing management decisions on one approach alone may lead scientists and managers to underestimate vulnerability.

Technical Summary

The overall goal of this project was to compare three different approaches for assessing vulnerability to climate change. We compared rankings of species vulnerabilities based on 1) niche-model-based changes in species distributions, 2) expert-opinion-based sensitivity and exposure, and 3) measures of climatic breadth (the variation in climate across a species current distribution) and climatic departure (the degree to which climates across a species' range are likely to diverge from current conditions). As a result of this project, we developed and produced the following.

1. Two new metrics for assessing vulnerability (climatic breadth and climatic departure).
2. Maps depicting spatial variation in climatic conditions (climatic breadth) across 400 species ranges.
3. Maps depicting the spatial distribution of vulnerability to climate change for 76 species based on both expert-opinion on climate-change sensitivities and projected changes in climate across species' ranges.
4. Rankings of species' vulnerabilities based on three different approaches to assessing vulnerability.

5. We also produced maps of projected changes in species' distributions and changes in vegetation—however these products were leveraged from other funding sources.

Purpose and Objectives

The objective of this study was to compare three different approaches to assessing the vulnerability to climate change of species in the Pacific Northwest. We compared the relative ranking of 76 species of vertebrates and plants with respect to their vulnerability to climatic changes forecast for the end of the century. Our project was designed to be useful to regional natural resource managers and specifically to aid in prioritizing species and locations for management actions in the face of climate change.

There were two minor departures from our original proposed objectives. First, we had proposed to examine both species and ecological systems. However, given the availability and quality of data on ecological systems, we decide to focus exclusively on species. Second, although we proposed to examine roughly 100 species, we were only able to rigorously examine 76 species across the three approaches due to the availability of data on species' sensitivities.

Figure 1. Study region.

Organization and Approach

This study was conducted over an area extending from northern California to northern British Columbia and from the west coast through Montana and Wyoming (Fig. 1). This region covers much of the Great Northern, North Pacific, and Great Basin LCCs, five states, and the majority of two provinces.

The approach we have taken is largely that described in the original proposal. However, we have 1) developed some new analytical methods (e.g., for calculating climate breadth) and 2) we have chosen to focus on species instead of species and ecological systems. We concluded that the data and models for ecological systems were not as robust as the data and models for individual species. We were also able to produce more models for individual species. In addition, as noted above, although we have analyzed 400 different species with at least one of the three approaches, due to incomplete expert-opinion-based species sensitivity accounts, we were unable to compare more than 76 species across the three approaches.

The three approaches included 1) projecting potential changes in species' distributions based on bioclimatic niche models, 2) a "sensitivity-exposure" approach which is a combination of an expert-opinion-based sensitivity assessment and projected changes in climate, and 3) calculating "climatic breadth" and "climatic departure"—measures of the diversity of climates a species currently occupies and the degree to which future climatic conditions across a species' range will likely differ from today's climatic conditions.

Climate data

We used historical climate data based on the CRU CL 2.0 (New et al., 2002) and CRU TS 2.1 (Mitchell and Jones 2005) climate data sets. These data were downscaled to a 10-minute latitude by 10-minute longitude global grid. For our study area, the CRU CL 2.0 and CRU TS 2.1 data were then further downscaled to a 30 arc-second (roughly 1-km^2) resolution grid using a geographic distance-weighted bilinear interpolation method (Shafer et al. 2011). We used a set of 23 bioclimatic variables averaged over a 30-year time period from 1961 to 1990. Projected future values for these same climatic variables, averaged over a 30-year time period spanning the years 2070 to 2099, were derived from two general circulation models (GCMs), the Canadian Centre for Climate Modeling and Analysis CGCM 3.1 model (Flato et al. 2000), and the UK Meteorology Office's Hadley CM3 model (Gordon et al. 2000) run for the A2 SRES emissions scenario. Both models project higher year-round temperatures by the end of the century, however, the models forecast two different potential climate regimes, one with high levels of precipitation year round and warmer winters (CGCM 3.1), and the other being slightly drier, but with intense, warm summers (Hadley CM3). The A2 emission scenario projects a mid-high level of future greenhouse-gas emissions.

Niche models

The first of the three assessment approaches involved building bioclimatic niche models for a set of species using projected future climates to forecast changes in species distributions. We used models built for 366 vertebrate species (12 amphibians, 237 birds, and 117 mammals) and 7 tree species. These models were developed as part of a larger Pacific Northwest Climate Change Vulnerability Assessment (www.climatevulnerability.org).

To build the models for the vertebrate species, we used digital range maps for mammals (Patterson et al. 2003), birds (Ridgely et al. 2003), and amphibians (IUCN 2012). We used a random forest algorithm (Breiman 2001), correlating known species range locations with the set of 23 bioclimatic variables to predict climate suitability at a coarse resolution (50-km x 50-km grid cells), spanning the entire ranges of each modeled species. The resulting coarse-resolution climate suitability models were then applied to the two finer resolution (1 km^2) projected climate datasets. We modified these "downscaled" projections of future climatic suitability with projections of future biome distributions (Rehfeldt et al. 2012) to produce projections of habitat suitability. For each species, we indexed terrestrial habitat associations described in the NatureServe Explorer online database records (NatureServe 2013) to develop species-biome relationships using the biome classifications developed by Rehfeldt et al. (2012). With these relationships as a guide, we classified each biome type as either suitable or unsuitable for each species. We then generated maps of biome-suitability for each species based on these classifications and the projected future biome distributions of Rehfeldt et al. (2012). For each species, we combined the map of projected biome-suitability with the map of projected climate suitability to produce a projection of habitat suitability. As a final refinement to these projections, for all non-synanthropic species, we reclassified areas dominated by urban, suburban, exurban and agricultural land-uses as being unsuitable. We classified species as being synanthropic or non-synanthropic based on habitat associations recorded in NatureServe Explorer.

For the tree species ranges, we downloaded digital maps from the U.S. Geological Survey "Atlas of United States Trees" (Little, 1971) and gridded them to the 1-km^2 resolution grid. As for the vertebrate species models, random forest algorithm was used to project potentially suitable climate space for the seven tree species. We refined these projections using the output of the Lund Potsdam Jena (LPJ) dynamic global vegetation model (DGVM). We limited projected future tree species distributions to corresponding projected biome types from the DGVM. LPJ is a process-based model that uses monthly temperature, precipitation, sunshine, annual atmospheric CO_2 concentrations, and soil data to simulate composition and structure of dominant vegetation in the form of plant functional types. LPJ was run with the climate data and climate projections described above.

We used the projected net change in a species' suitable climate space as the measure of vulnerability. We have calculated these net changes for all species under the two different climate-change scenarios (the CGCM 3.1 and Hadley CM3 model projections, both based on the A2 emissions scenario).

Sensitivity-Exposure

Our second approach to assessing vulnerability to climate change involved combining expert-opinion-based estimates of species' sensitivities to climate change with projected changes in climate across species' distributions. We applied this approach to 76 species of vertebrates and trees.

We extracted expert-opinion-based sensitivity estimates from the Climate Change Sensitivity Database (CCSD – www.climatechangesensitivity.org). This digital database uses a combination of expert review panels, literature searches and digital databases to summarize the inherent climate sensitivities for species and habitats of concern throughout the Pacific Northwest and was developed as part of the larger Pacific Northwest Climate Change Vulnerability Assessment. The database provides resource managers and decision makers with basic information about how species will likely respond to climate change based on the following factors: degree to which the species is a generalist/specialist, physiology, life history, habitat, dispersal ability, disturbance regimes, ecology, and non-climate related threats. Species experts assign each species a numeric ranking (1 being the least sensitive and 7 being the most sensitive to climate change) for each of these factors based on best available science. Additional specific questions are included for each category to highlight particular life-history characteristics that drive climate-change sensitivity. For example, the average length of time to reproductive maturity has the potential to influence a species' ability to adapt to changing conditions.

Here, we used the raw scores for each factor and additional information recorded in the database about the specific climatic drivers of physiological and habitat-based sensitivity to climate change. The database allowed experts to specify individual scores for temperature and precipitation sensitivities. In addition, experts could mention whether a species was particularly sensitive to changes in snow pack. We were therefore able to rank sensitivity to these three specific climate variables (temperature change, precipitation/moisture, and a proxy for snow pack) individually. Experts also listed any habitats upon which a species depended that were themselves highly sensitive to climate change. We used this information, in conjunction with the LPJ-based projections of biome shifts to assess potential vulnerability based on habitat associations.

We developed analogous measures of climate change exposure for each sensitivity category (Table 1). These included projections of relevant direct and derived climate variables, a measure of overall climate change across seasonal temperature and precipitation (Standard Euclidean Distance or SED), projected changes to vegetation types, and the impact of human land-use patterns as measure by the human footprint. All exposure variables were scaled to be between 0 and 1 with 1 being the highest level of exposure and 0 being no exposure (or no change). Many exposure measures ranged from 0 to 1 in their raw values (for example future snow pack was measured as a proportion of current snowpack). Ideally, exposure would be scaled depending on the ecological impact of a given unit of change. However, such information is not generally available and likely unique to each species. To assess how sensitive our results were to re-scaling, we calculated vulnerability scores with raw as well as ranked data.

Table 1. Sensitivity and corresponding exposure metrics used to calculate vulnerability to climate change using the "sensitivity-exposure" approach.

Sensitivity Category	**Description**	**Exposure Measure**
Generalist/ Specialist	Broadly, where does this species fall on the spectrum of generalist to specialist? Specialists are considered more sensitive to climate change than generalists	Overall climate change (SED)
Physiology - Temperature	Physiological sensitivity is directly related to a species' physiological ability to tolerate changes in temperature, precipitation, salinity, pH, and CO2 that are higher or lower than the range that they currently experience. If a species can tolerate a wide range of these variables, it would be deemed less sensitive.	Projected temperature change: 0.0-3.9 = 0.2, 3.9 - 4.1 = 0.4, 4.1-4.2 = 0.6, 4.2-4.6 = 0.8, 4.6-6.0 = 1
Physiology - Moisture/ Precipitation		Absolute value of the projected change in Moisture Index
Physiology - Snow		% decrease in precipitation as snow. Maximum exposure = 100% loss.
Life History	Reproductive life history characteristics that may affect adaptive capacity including r-selection (many offspring, short generation time) versus k-selection (few offspring, high parental investment) reproduction strategies, frequency and timing of reproduction and length of time to reproductive maturity.	Overall climate change (SED)
Habitat - Alpine/Subalpine	Is the species dependent on climate sensitive habitats? How dependent?	Projected loss of alpine/subalpine habitat based on DGVM
Habitat - Grassland		Projected loss of grassland habitat based on DGVM
Habitat - Wetland/Aquatic		In high elevation forest habitats - increased summer AET = increased exposure; in low elevation habitats decreased spring AET = increased exposure
Dispersal Ability	The maximum average distance a species will likely move with in one year to establish a new population in a more suitable habitat. Are there landscape elements that would prevent this species from moving in response to climate change?	Overall climate change (SED)
Disturbance Regimes	Is the species sensitive to different types of disturbance (e.g. fire, flooding, disease) that may be affected by climate change. This relationship may be either positive or negative.	Overall climate change (SED)
Ecology	How sensitive are ecological relationships such as foraging, predator prey relationships, and competition to climate change?	Overall climate change (SED)
Interacting Non-climatic Stressors	What other stressors may make this species more sensitive to climate change (e.g. habitat loss, invasive species competition, etc.)?	Overall climate change (SED)
Other (weight)	Any other factor not previously mentioned that would affect this species sensitivity to climate change.	

We calculated vulnerability for each species by multiplying a species' sensitivity score for each category by the appropriate exposure variable. This calculation resulted in a map of vulnerability for each species, with a resolution of ~ 1-km, across the species' range. Because the sensitivity score is a constant, spatial variability in the map was due to exposure alone. Each sensitivity category was calculated separately. Because sensitivity scores ranged from 0 to 7 and exposure scores ranged from 0 to 1, maximum vulnerability for each sensitivity category was 7. We calculated vulnerability as:

Vulnerability = ((1/2 * Generalist/Specialist) + Temp + Moisture + Snowpack + (1/2 * Life History) + Sensitive Habitats + Dispersal Ability + Disturbance Regimes + Ecological Relationships + Interacting Non-Climatic Stressors) / 63

We weighted the Generalist/Specialist and Life History categories less than other categories in part due to the many discussions that we had with experts about the relative importance of each sensitivity factor. In addition, we calculated vulnerability with and without including habitat exposure, because vegetation projections are highly uncertain and because our assessment of wetland impact may miss important thresholds of change or other impacts that affect wetland habitat suitability.

Once vulnerability was calculated for each species throughout the study area, vulnerability within each species' range was summarized by calculating the mean and maximum vulnerability for each species across its current range. Species were ranked from most to least vulnerable for each of the three composite vulnerability scores using the mean within-range vulnerability score. These rankings were compared using spearman rank correlation.

Climatic breadth and climatic departure

Our third approach to assessing climate vulnerability was based on measures of climatic breadth and climatic departure. These are two novel metrics developed for this study. Climatic breadth assesses multivariate variance in climate across a species' range. Climatic departure estimates the difference between the current climate and the projected future climate across a species' range. Species with narrow climate breadths are likely to be most sensitive to changes in climate because they may only be adapted to a narrow range of climates. Species with large climatic departures are likely to be more vulnerable to climate change because the climates within their current distribution will be substantially different from the climates they experience today.

For our calculations of climatic breadth and climatic departure reported on here, we used a different climate data set. We used data consisting of 40 annual, seasonal, and monthly bioclimatic variables from the Climate WNA database (Wang *et al.*, 2012), based on the PRISM dataset (Daly *et al.*, 2002), and downscaled to a 1-km^2 resolution. The historical dataset was based on averaged climate records from 1961-1990. The future datasets consisted of climate projections from three different GCMs (BCCR BCM2.0, CCCMA CGCM3, CSIRO MK 3.0) run for the SRES A2 greenhouse-gas emissions scenario (Solomon *et al.*, 2007). The study area covered much of the western half of North America, from 25–60˚N and 140–100˚W. We are currently in the process of re-running the climatic breadth and climatic departure analyses using the same climate data used in the niche models and the sensitivity-exposure based assessment to make the approaches more comparable. Although the updated analyses have the potential to produce different estimates of climatic departure for the 37 species that we compared across the three vulnerability measures, our estimates of climatic breadth are likely to be largely unchanged because they are based on recent historical climate and although the historical climate datasets may differ slightly due to differences in downscaling, these differences will be minor compared to those associated with projections from different GCMs. For this reason, and because the measures of climatic breadth and climatic departure were relatively highly correlated, we used climatic breadth in our comparison of the 37 species here.

We used digital maps of species' distributions (the same range maps used in the other assessments) in conjunction with data from multiple climate datasets to measure both climatic breadth and climatic departure for 400 species of vertebrates and trees.

Before calculating climatic breadth and departure, we used principal component analysis (PCA) to minimize the correlation between the climate variables, and to center and scale them appropriately (Jolliffe, 2005). The number of significant components was determined using Frontier's broken-stick method (Jackson, 1993), which produced two PCA-transformed variables that collectively accounted for 85.9% of the variation of our original climate data. To maintain consistency across datasets, we used the loadings of the historical PCA to transform the future data.

To assess climatic breadth for each species, we calculated the median of each of the PCA-transformed climate variables across the species' geographic range. We then calculated the Euclidean distance between the historical climate values and the historical climate medians for every data point within the species distribution, and scaled it to the entire study area. This process yielded a value for each point inside the distribution that reflected the difference between that point and the median climatic conditions across the species range. We define climate breadth as the median of these distances. This is written formally as

$\sigma c = \text{Median} 100 i \in C(xi - \mu i)2|IQR|$

where σ_c is the climate breadth, C is the set of significant PCA components, x_i is in the set P of raster cells indicating presence of the species, μi is the median value of variable i over P, $|IQR|$ is the Euclidean distance between the first and third quartiles of the entire climate dataset for each variable i. Climate breadth is similar to the median absolute deviation (a robust measure of central tendency), but extended to accommodate higher-dimensional data and normalized for the study area (Donoho & Huber, 1983).

To measure climatic departure, we calculated the Euclidean distance between the future climate values and the historical climate medians for every data point within the species range. This yielded a second set of distances that collectively described the difference between future climatic conditions and the historical medians across a geographic distribution. We then calculated the lack of overlap (or departure), between density plots of the historical distances and density plots of the future distances. Species with less overlap in the r current and future density plots were determined to have higher climatic departures and thus likely be more vulnerable to climate change.

Vulnerability-assessment comparison
We compared the relative ranking of species based on their vulnerabilities as assessed by the three different approaches using Spearman rank correlations and by examining the list of highly ranked species produced by each of the three approaches.

Project Results

Niche models

Species showed a significant range of projected changes in the distribution of climatically suitable areas and these changes often differ substantially between the two climate models used in these analyses (Fig. 2). We used the model projections to estimate net changes in the climatically suitable area for each species under each projected future climate and ranked the species based on projected net changes—the most vulnerable species having the largest net losses and the least having the largest net gains. Projected net changes across all species ranged from a 12-fold increase in climatically suitable area to a complete loss of climatically suitable area.

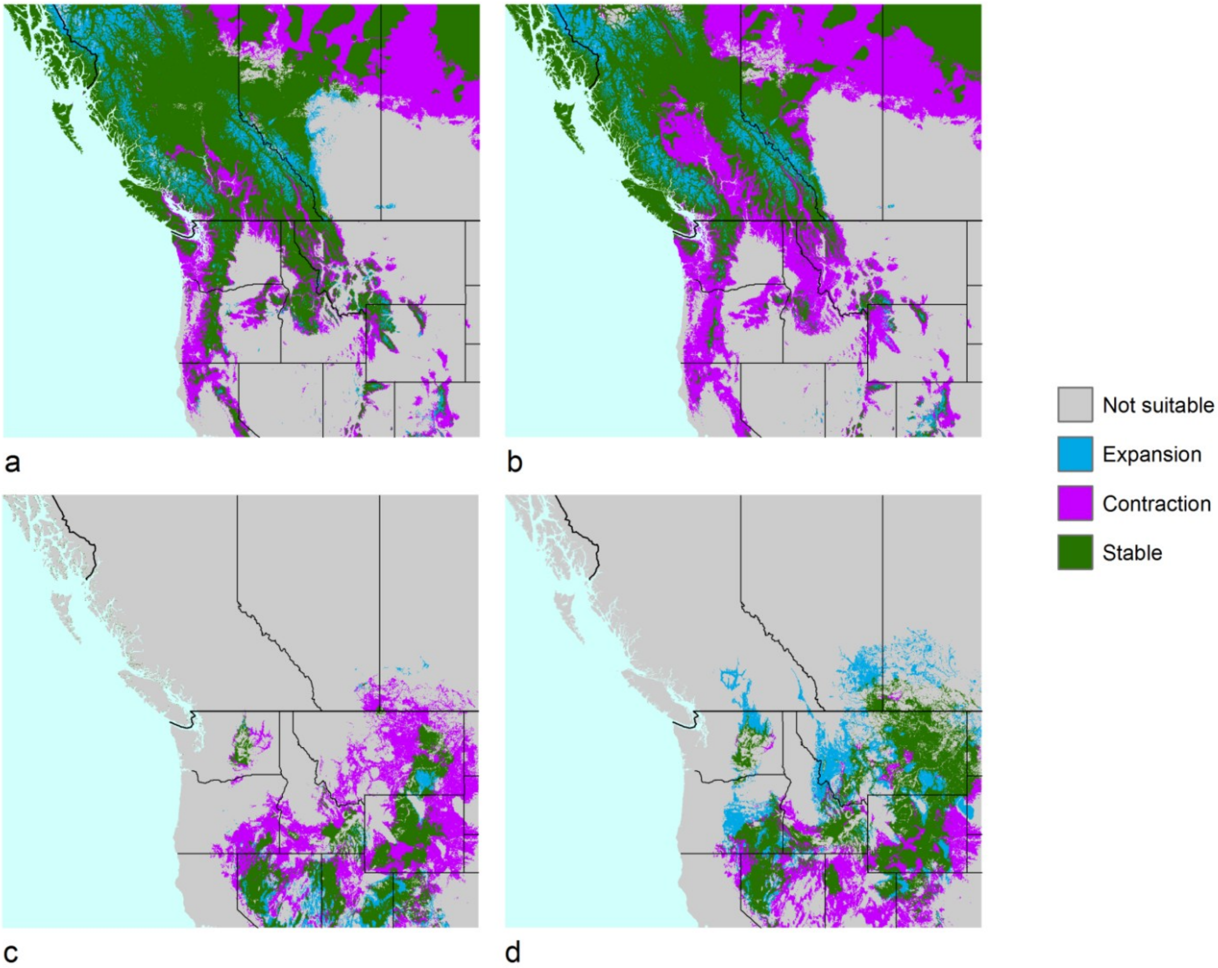


Figure 2. Predicted future change in habitat suitability based on the CGCM3.1 and Hadley CM3 projections for the Northern Goshawk (*Accipiter gentilis*), (a and b respectively), and the Greater Sage Grouse (*Centrocercus urophasianus*), (c and d, respectively).

Sensitivity-Exposure

We evaluated sensitivity-exposure based vulnerability for 76 species including 2 amphibians, 60 birds, 8 mammals, and 6 tree species. This final list was the total number of species for which we had complete entries in the sensitivity database, finalized climatic niche models, and climate breadth calculations. Total sensitivity scores for these species ranged from 22 to 81 with a median value of 51. To place these numbers in context, the maximum sensitivity score in the database was 90, with median scores of 76 for amphibians, 52 for birds, 54 for mammals, and 48 for plants. We note that there were eight highly sensitive species in the species sensitivity database that are missing from this study, seven of these are amphibians and one is a plant. Because climatic niche models had not been built for these species, we did not include them in this analysis.

Vulnerability based on expert-opinion-based sensitivity and the multiple measures of exposures based on projected changes in climate, vegetation, and current land-use (human footprint) resulted in maximum vulnerability scores (the maximum score found across a species' range) that ranged from 0.15 (American Crow, *Corvus brachyrhynchos*) to 0.61 (Caribou, *Rangifer tarandus*) both under the CGCM3.1 climate scenario. Mean within range total vulnerability was lower, ranging from 0.07 (Cassin's Auklet, *Ptychoramphus aleuticus* – Hadley) to 0.44 (Caribou – CGCM3.1). Vulnerability also ranged significantly across species' distributions (e.g., Fig. 3). Not surprisingly, vulnerability was strongly correlated with sensitivity scores. Correlation between maximum within range total vulnerability and sensitivity was 0.90. Correlation between mean within range total vulnerability and sensitivity was 0.70-0.78.

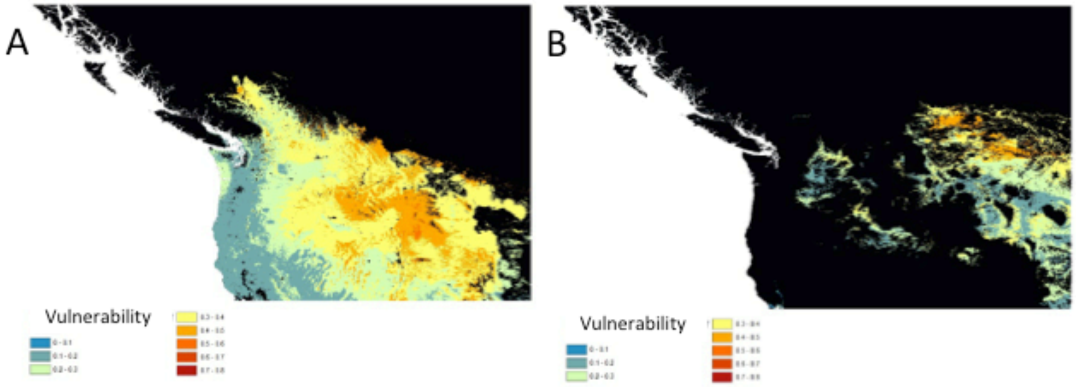


Figure 3. Mapped vulnerability scores for A) Townsend's western big-eared bat (*Corynorhinus townsendii)* and B) grasshopper sparrow (*Ammodramus savannarum*). Blue colors represent lower vulnerabilities and orange and red colors represent higher vulnerabilities.

Although the contribution to the total vulnerability score often varied dramatically across the different factors for a given species (Fig. 4), the ranking of species based on this measure of vulnerability was relatively robust to changes in the formulation of the metric. We explored different formulations that excluded specific pairs of sensitivity and exposure factors. Correlations among these different formulations were generally high (mean *r* = 0.72).

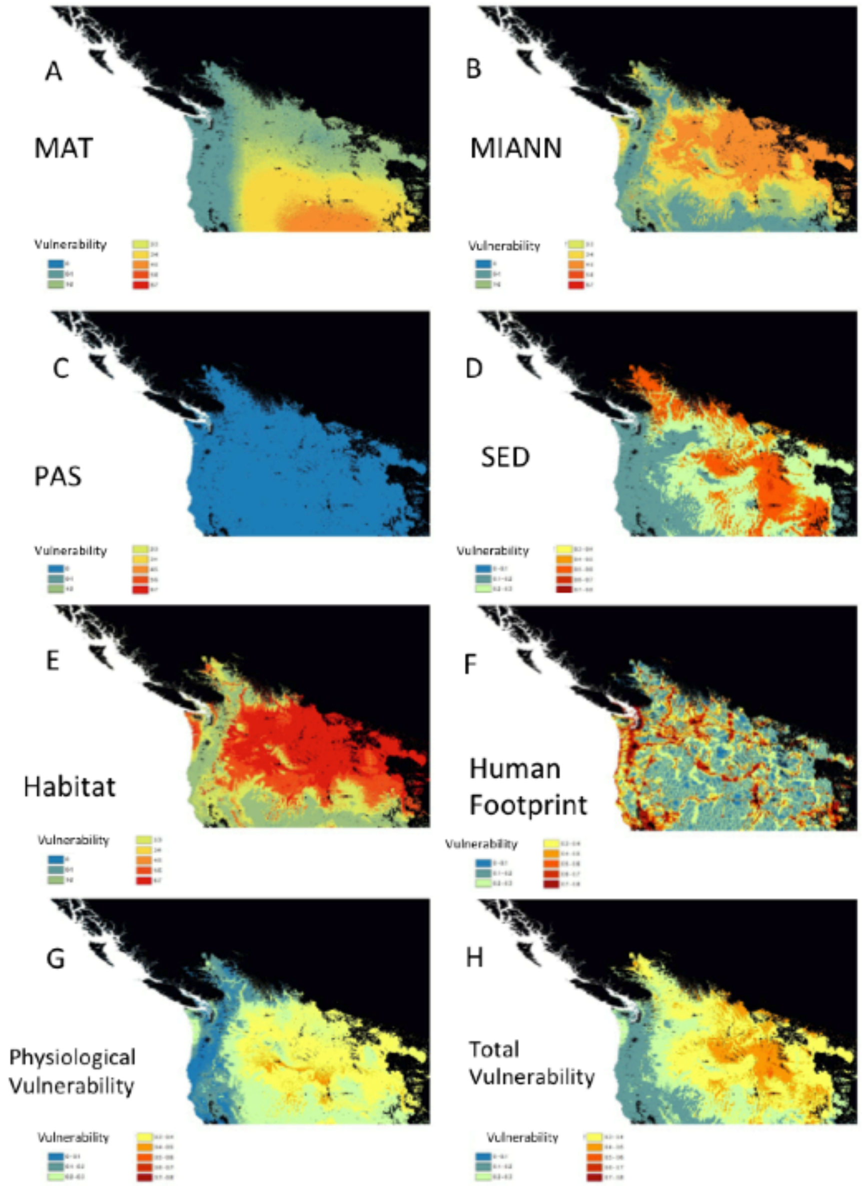
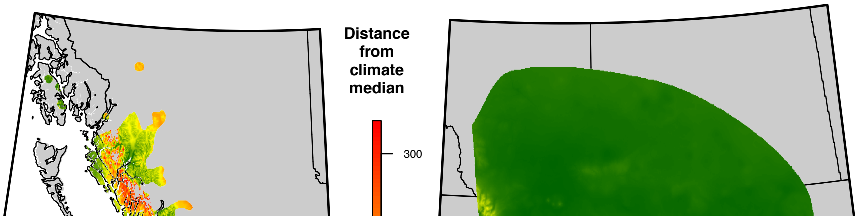
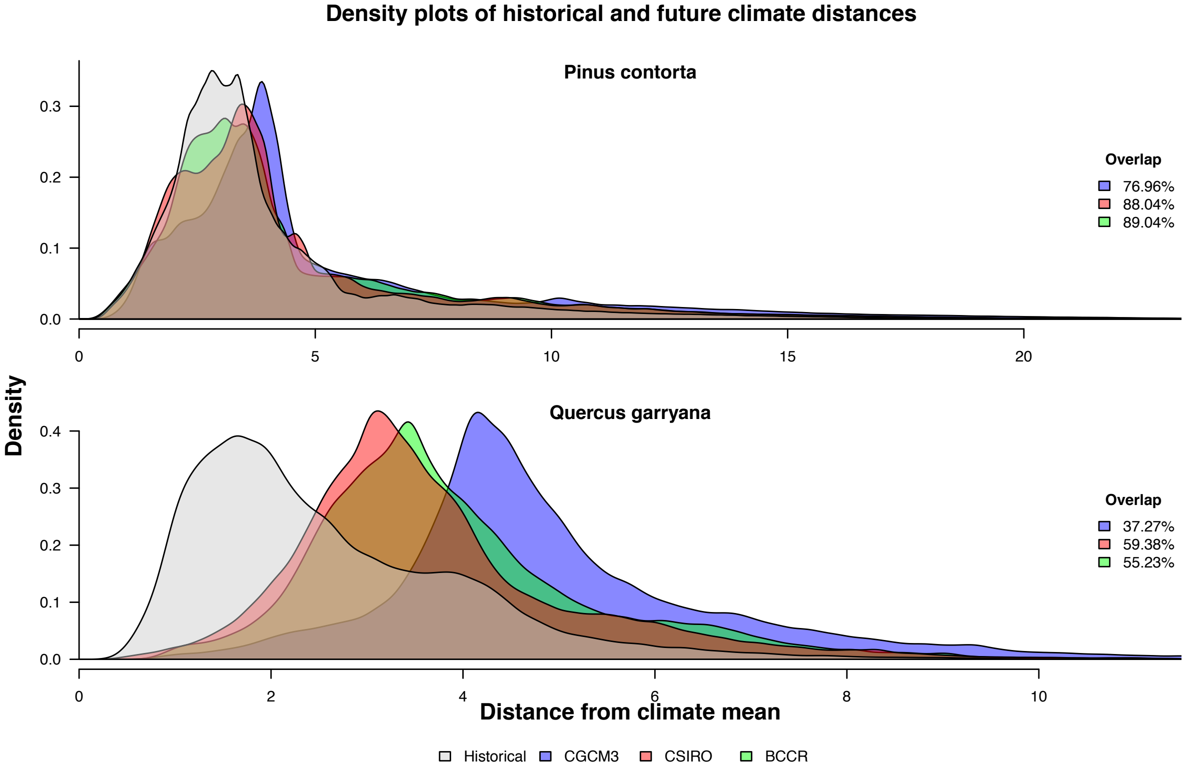


Figure 4. Mapped components of vulnerability for Townsend's western big-eared bat (*Corynorhinus townsendii*). Components include vulnerabilities due to A) mean annual temperature, B) minimum annual temperature, C) snow pack, D) multivariate estimate of climate change, E) highly sensitive habitats, F) effects of human dominated landscapes on potential dispersal, G) aspects of physiology, and H) all components combined.

Climatic breadth

We calculated climatic breadth and climatic departure for a total of 400 species. Both measures varied substantially across species (e.g., Figs. 5 and 6). Whereas some species occupied a relatively wide range of climates (e.g., Pacific silver fir, *Abies amabalis*, Fig. 5a) others had relatively narrow climatic niches (e.g., McCown's longspur, *Rhynchophanes mccownii*, Fig. 5b). Similarly, species varied in their degree of climatic depature they were projected to experience. For example lodgepole pine (*Pinus contorta*) was projected to have relatively little climatic departure (Fig. 6a) compared to Oregon white oak (*Quercus garryana*, Fig. 6b). The two measures (climatic breadth and climatic departure) were, as expected, relatively highly correlated ($r = 0.90$).





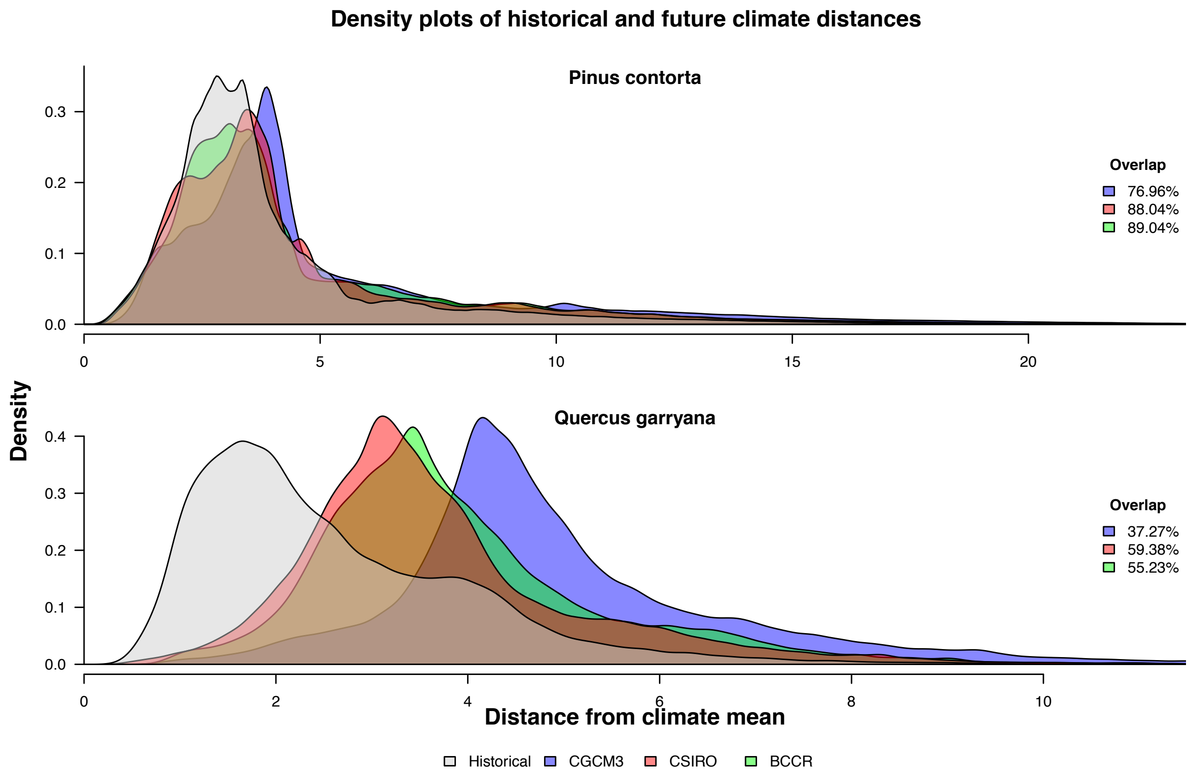


Figure 6. Climatic departure as depicted by the distribution of historical (grey) and projected future (blue, red, and green) distances in multivariate space from the species' multivariate average historical climate for lodgepole pine (*Pinus contorta*) and Oregon white oak (*Quercus garryana*). The less overlap in the historical and projected future climatic distances, the higher the climatic departure and the more vulnerable to climate change a species is likely to be.

Comparing the three approaches

Rankings of the 76 species based on the three different approaches to assessing vulnerability differed substantially. Correlations of the species ranks across the three approaches were weak, ranging from 0.23 to 0.36 (Table 2). However, rankings of species by a single approach using data from two different climate-model projections (e.g., niche model projections based on the CGCM3.1 and the Hadley CM3 models) were quite similar (Table 2). Only one species, the caribou (*Rangifer tarandus*), was ranked in the top ten most vulnerable species by all three approaches (Table 3). By contrast, eight of the ten species ranked as most vulnerable by the niche modeling approach based on the two different climate change projections, and seven of the top ten most vulnerable species as ranked by the sensitivity-exposure approach based on the two climate projections, overlapped (Table 3).

Table 2. Spearman correlations among the rankings of species across three approaches to assessing vulnerability. The niche-model and the sensitivity-exposure approaches were assessed using two different future climate-change projections (the CGCM3.a GCM and the Hadley CM3 GCM).

	Climatic breadth	Niche model (CGCM3.1)	Niche model (hadCM3)	Sensitivity-Exposure-Based Vulnerability (CGCM3.1)	Sensitivity-Exposure-Based Vulnerability (hadCM3)
Climatic breadth	1	0.30	0.23	0.36	0.28
Niche model (CGCM3.1)		1	0.93	0.25	0.23
Niche model (hadCM3)			1	0.31	0.26
Sensitivity-Exposure-Based Vulnerability (CGCM3.1)				1	0.89

Table 3. Ten most vulnerable species as ranked by three different approaches. Rankings for the sensitivity-exposure and niche-model approaches based on data from both the CGCM3.1 and Hadley CM3 GCM climate projections are included.

Niche model (CGCM3.1)	Niche model (hadCM3)	Sensitivity-Exposure-Based Vulnerability (CGCM3.1)	Sensitivity-Exposure-Based Vulnerability (hadCM3)	Climatic breadth
Pacific Loon	Cassin's Finch	Caribou	Townsend's Western Big-eared Bat	Yellow Rail
Caribou	White-faced Ibis	Townsend's Western Big-eared Bat	Cassin's Finch	Caribou
White-faced Ibis	Caribou	Northern Bog Lemming	Snowy Egret	Greater Sage Grouse
American Pipit	Gray-crowned Rosy-Finch	Western Grebe	Western Grebe	California Gull
Gray-crowned Rosy-Finch	American Pipit	Grasshopper Sparrow	Northern Red-legged Frog	Gray-crowned Rosy-Finch
Pinyon Jay	Western Bluebird	Cassin's Finch	Boreal Owl	Ferruginous Hawk
Green-tailed Towhee	Dusky Grouse	Boreal Owl	Northern Goshawk	Sage Thrasher
Dusky Grouse	Red-naped Sapsucker	Ruffed Grouse	Western Bluebird	Pinyon Jay
Cassin's Finch	Green-tailed Towhee	American Pipit	Caribou	Green-tailed Towhee
Ringtail	Clark's Nutcracker	Northern Goshawk	American Pipit	Barred Owl

Analysis and Findings

1. *A new approach for assessing vulnerability to climate change.* We produced two new metrics for assessing the potential effects of climate change on species. **Climatic breadth** measures the degree to which climatic conditions vary across a species' range—with the assumption that species with narrow climatic breadths will be more sensitive to climate change. **Climatic departure** measures the

degree to which the climate currently experienced by a species will likely change across its range. Species with future climates that differ more from their current climate are likely to be more vulnerable to climate change than species with future climates similar to those they exist in today because they will likely need to adapt or move in response to changing conditions. These measures are useful because they rely only on species distribution data and climate data and they make fewer assumptions about species' biology than do climatic niche models.

2. *Different approaches to assessing vulnerability provide markedly different results.* We found that approaches based on niche models (the most commonly used tool for assessing climate impacts), climatic breadth, and expert-opinion-based sensitivity and exposure produced substantially different assessments of species' vulnerabilities. It is perhaps not surprising that these three approaches produced substantially different vulnerability rankings. The projected changes in species distributions based on climatic niche models use projected future climatic conditions to assess what portion of a species range might become unsuitable. These models don't account for specific aspects of species biology such as dispersal ability, reproductive strategy, dependence on climate-sensitive habitats or on specific disturbance regimes. Thus, it is not surprising that the niche projections and the expert-opinion-based sensitivity-exposure approach produced markedly different rankings. What is perhaps a little more surprising is that the niche-modeling approach and the climatic breadth-based approach provided such different rankings. Both of these metrics are in part dependent on the range of current climatic conditions across a species range and thus one would expect higher correlation between vulnerability rankings based on the two metrics than we found.

3. *Vulnerability assessments are likely to be more robust to variability in climate-change projections than to assessment approaches.* Although we only explored assessments based on two different climate-change projections (from the CGCM3.1 and the Hadley CM3 model) we found that vulnerability rankings based on niche-model projections under the two projections and rankings based on sensitivity-exposure rankings based on the two projections were similar.

Conclusions and Recommendations

Perhaps the most important conclusion that can be drawn from our study is that planners and managers should not rely on a single measure of vulnerability. Our results show that by examining projected changes in species' distributions, expert knowledge of species' sensitivities, and current climate breadths occupied by species can lead to very different conclusions about how vulnerable species are likely to be to climate change. A more robust approach to assessing vulnerability would draw on multiple lines of evidence. For example, overlaying maps of projected range shifts, sensitivity-exposure-based vulnerability, and climatic breadth or exposure would provide an estimate of where anyone of the three approaches project high vulnerability and where all three of the approaches project lower vulnerability.

Our results also highlight the fact that vulnerability assessments are likely to be relatively robust despite a range of future climate projections. Thus managers and planners may need to worry less about the diversity of future climate-change projections than they do about exploring multiple indicators of vulnerability. However, it is important to note that our comparison only drew on two different climate-change projections—had we explored more projections, it is possible that we may have found greater differences and would have concluded that it was more important to consider multiple future climates when assessing vulnerability.

Although we had aimed to compare vulnerabilities of over 100 species using the three approaches, we were only able to fully analyze 76 species. This was in part due to a lack of key information in the species sensitivity database and our inability to build well-fitting niche models for as many species as we had anticipated. In addition, early on in the project, we decided to focus exclusively on species vulnerabilities and not on ecological systems. We found that we had much better data for individual species than we did for ecological systems. Finally, one of the products that we listed in our original project proposal was cross-boarder climate-change induced vegetation-change projections. These were being produced as part of the larger Pacific Northwest Climate Change Vulnerability Assessment. We did, indeed incorporate these projections into some of our niche modeling as well as into our sensitivity-exposure-based approach. However, as of the writing of this report, our USGS collaborator has still not released these data to the public and so we are unable to deliver these data layers at this time. When they become available, we will provide a link to these layers on the Pacific Northwest Climate Change Vulnerability Assessment website.

In the results presented here, we used our new metric of climatic breadth. We are still working on comparisons of the three approaches that draw on the more comprehensive measure of climatic departure. We have finished the calculations of climatic departure, but have not, to date, compared vulnerabilities a based on these rankings. This is a next step.

Management Applications and Products

The work described here is part of the larger Pacific Northwest Climate Change Vulnerability Assessment. The larger project was designed and executed in collaboration with mangers and scientists at The Nature Conservancy (Elizabeth Gray), the Washington Department of Fish and Wildlife (Rocky Beach [retired], Bruce Thompson), Idaho Fish and Game (Leona Svencara), and USGS (J. Michael Scott and Sarah Shafer). Some of the individual products of the this project have fed into the state wildlife action plans of Idaho Fish and Game Department and have been used by the Arid Lands Initiative in eastern Washington. In addition, some of the estimates of sensitivity have been used by the US Forest Service (Crystal Raymond, David Peterson) and National Park Service (Regina Rochefort) in regional adaptation planning efforts. Due to their relatively recent completion, neither the climatic breadth nor the synthetic comparison of approaches have yet been used in any management or planning activities.

Outreach

To date, our outreach efforts have included, eight presentations, five papers that are either in review or are in preparation, and a contribution to a NWF report. We have plans to share the results of these analyses with the North Pacific, Great Northern, and Great Basin LCCs as well as with Idaho Fish and Game and the Washington Department of Fish and Wildlife through our collaborators in those two agencies.

Presentations
Case, M. J., J. J. Lawler, and J. Tomasevic. 2014. Relative climate change sensitivity of species in the Pacific Northwest. Pacific Northwest Climate Conference, Seattle.

Michalak, J. L. 2014. Evaluating Climate Change Vulnerability in the Pacific Northwest: Integrated Assessments of Potential Ecological Change in Three Case Study Landscapes. Pacific Northwest Climate Conference, Seattle.

Rinnan, S. D., 2014. Quantifying Sensitivity and exposure to climate change in western North American Species. Pacific Northwest Climate Science Conference, Seattle.

Rinnan, S. D., 2014. Quantifying Sensitivity and exposure to climate change in western North American Species. School of Forestry and Environmental Sciences Graduate Student Symposium, Seattle.

Rinnan, S. D. 2014. Quantifying Sensitivity and exposure to climate change in western North American Species. Quantitative Ecology and Resource Management Seminar, Seattle.

Rinnan, S. D. 2014. Quantifying Sensitivity and exposure to climate change in western North American Species. Max Planck Institute for Ornithology, Germany.

Case, M. J. 2014. Climate-related risks for Western forests, Northwest Wood-Based Biofuels + Co-Products Conference, Seattle.

Case, M. J. 2013. Adaptation options for forested systems in the Sierra Nevada. Sierra Nevada Vulnerability Assessment and Adaptation Strategies workshop. Sacramento, CA.

Journal articles (in review and preparation)
Langdon, J. G. R. and J. J. Lawler. *In review.* Assessing the impacts of projected climate change on biodiversity in the protected areas of western North America. *Ecosphere*.

Case, M. J. and J. J. Lawler. *In review.* Relative sensitivity to climate change of species in the Pacific Northwest, North America. *Biological Conservation*.

Rinnan, D. S. and J. J. Lawler. *In preparation.* Using climate breadth to quantify species vulnerability to climate change. Target journal: *Global Change Biology.*

Michalak, J. L., M. J. Case, J. G. R. Langdon, D. S. Rinnan, R. Beach, E. Gray, F. Saltre, J. M. Scott, S. Shafer, L. Svencara, B. Thompson, and J. J. Lawler. *In preparation.* Comparing three approaches to assessing species vulnerability to climate change. Target journal: *Global Change Biology.*

Michalak, J. L., M. J. Case, and J. J. Lawler. *In preparation.* Sensitivity, exposure, and vulnerability of species to climate change. Target journal: *Conservation Biology.*

Other publications
Glick, P., L. Helbrecht, J. J. Lawler, and M. J. Case. 2013. *Safeguarding Washington's Fish and Wildlife in an Era of Climate Change: A Case Study of Partnerships in Action*, National Wildlife Federation, Seattle, WA.

Data
Maps and vulnerability rankings of all species will be made available on line.

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