esa

ECOSPHERE

Assessing the impacts of projected climate change on biodiversity in the protected areas of western North America

Jesse G. R. Langdon[1,]† and Joshua J. Lawler

School of Environmental and Forest Sciences, University of Washington, Seattle, Washington 98195 USA

Citation: Langdon, J. G. R., and J. J. Lawler. 2015. Assessing the impacts of projected climate change on biodiversity in the protected areas of western North America. Ecosphere 6(5):87. http://dx.doi.org/10.1890/ES14-00400.1

Abstract. Protected areas are a fundamental component of many conservation strategies. They safeguard some of the best examples of unfragmented natural landscapes in many regions, provide important habitat for rare and threatened species, and serve as a refuge from a human-dominated world. As climates continue to change, species distributions, ecological communities, and ecosystems will be altered. An understanding of the trends in these changes can allow protected area managers to develop more effective climate-adaptation strategies. Here, we quantify the relative amount of projected potential climate-driven ecological change across a protected area network by calculating three metrics. We assessed future projected changes in temperature and precipitation, shifts in major vegetation types, and vertebrate species turnover for the protected areas of the Pacific Northwestern region of North America. In general, the degree of projected change in the three metrics followed a longitudinal gradient from the Pacific coast inland toward the continental interior. Protected areas expected to experience the least change are at low elevations near the coast and throughout the Coastal Mountains, whereas areas expected to experience the most change are found at higher elevations in the Rocky Mountains and Great Basin regions. The resulting spatial variation in these impact measures underscores the importance of developing appropriate, location-specific, climate-adaptation strategies in response to disparate trends in future environmental change.

Key words: biodiversity; biome shift; climate adaptation; climate change; climate projections; habitat suitability; protected areas; species turnover; vegetation change.

Received 17 October 2014; revised 5 December 2014; accepted 23 December 2014; final version received 2 April 2015; **published** 29 May 2015. Corresponding Editor: D. P. C. Peters.

[1] Present address: South Fork Research, Inc., North Bend, Washington 98045 USA.

† **E-mail:** jesselangdon@gmail.com

Introduction

Current and future changes in climatic conditions represent a major challenge for natural resource managers. Shifts in species ranges have already been observed (Chen et al. 2011), and continued shifts in species distributions have been consistently projected in response to predicted future changes in climate suitability (Araújo et al. 2005, Thuiller et al. 2005) and shifts in human land-use patterns (Pekin and Pijanowski 2012). The formation of novel climates and no-analog biological communities is expected (Williams and Jackson 2007*a*), with the potential for novel climatic conditions to cover between 12% and 39% of the terrestrial surface of the earth by the end of this century (Williams et al. 2007*b*).

Protected areas can play a critical role in conserving biodiversity in a changing climate (Hannah et al. 2007). These areas often contain the only remaining large contiguous patches of natural land cover in a region, providing critical habitat for sensitive species and helping to maintain intact, functioning ecosystems. Given their current distribution, protected areas may be more likely to harbor favorable climate conditions for species in the future than will unprotected areas (Araújo et al. 2011), and they have been shown to be disproportionately important for species expanding their ranges and colonizing newly suitable areas in response to climate change (Thomas et al. 2012).

Nonetheless, many protected areas will become less climatically suitable for some species, and as a result, those species, may be less well represented in protected areas in the future (Araújo et al. 2004, Hannah et al. 2005). In particular, it has been suggested that small protected areas, protected areas at higher latitudes, and protected areas characterized by extensive alpine areas, coastal habitats, wetlands, abrupt land-use transitions, or by a large numbers of species at the latitudinal limits of their geographic ranges are likely to be particularly vulnerable to the loss of species and ecological systems (Shafer 1999). In addition, protected areas with little climatic diversity or in areas with high projected climatic velocities (e.g., Loarie et al. 2009, Dobrowski et al. 2013) are likely to be more vulnerable to change. Climatic diversity is higher, and climatic velocities are lower in areas with more topographic relief, implying that protected areas in flatter landscapes will, all else being equal, be more vulnerable to climate change. But, all else is not equal, and the relative risk posed to the biota of a protected area will also depend on the degree of environmental change the protected area is likely to experience (including changes in climate, habitats, and disturbance regimes). Understanding which protected areas will likely see the most and the least climate-driven ecological change can help managers and planners allocate scarce resources towards their management.

Here, we explore the relative projected impact of climate change on sites within a protected area network in western North America. We used three measures of projected change to assess potential impacts—changes in climate, shifts in vegetation, and species turnover. We assessed projected changes in climate using a multivariate estimate of dissimilarity between current and projected future climates, and shifts in vegetation and species turnover using modeled changes in biome and vertebrate species distributions, respectively. We used the three measures to rank all protected areas within the network by potential future climate impacts.

Methods

Study area

This study covered the Pacific Northwest region of North America—a 6,895,788-km^2 area including a broad range of climates, biomes, and topography, extending from $-136°$ W to $-102°$ W longitude and from 58° N to 38° N latitude (Fig. 1). Elevation in the region ranges from sea level to 4394 m and the area spans alpine tundra, subalpine grasslands and forests, wet and dry montane and low-elevation forests, temperate grasslands, and arid shrublands and desert.

Data sources

All data were mapped to a grid comprised of 30-second $\times$ 30-second (approximately 1-km^2) cells. This resolution was fine enough to capture local variations in the climatic and ecological measures and to provide a relatively accurate portrayal of the protected area network.

We mapped protected areas using the World Database of Protected Areas (WDPA) (IUCN and UNEP 2010). WDPA protected areas are organized by IUCN Protected Area Management Categories according to consistencies in management approach and intent (Dudley 2008). We selected only those areas with an IUCN category of Ia, Ib, II, III, or IV. These categories include areas for which the primary management objective is protection of species or ecosystems. Protected areas categorized as V or VI, which were not included in the study, are comprised of areas with multiple management objectives, including maintenance of traditional resource extraction and protection of important cultural resources and services. For protected areas comprised of disconnected parcels of land that spanned relatively large geographic areas, we considered each parcel as a separate protected area. We then selected only those protected areas with a total area greater than or equal to 10 km^2, to minimize the potential for a mismatch between the 1-km^2 grid cells and the protected area boundaries. We then mapped the resulting WDPA protected areas to the 1-km^2 resolution grid. The final protected area data set included

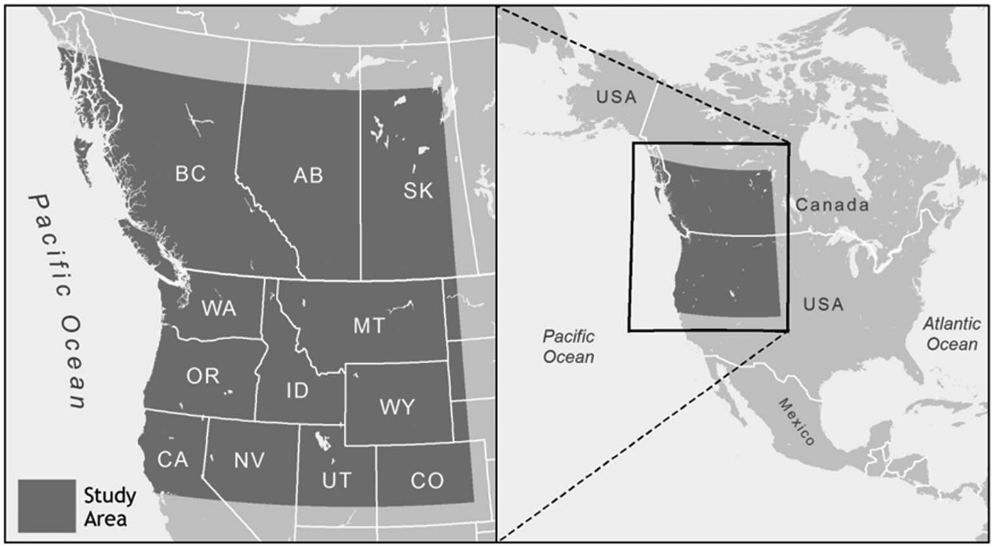

Fig. 1. The study area, which spans the international border between Canada and the United States. The area encompasses five states, including Washington (WA), Oregon (OR), Idaho (ID), Montana (MT), and Wyoming (WY), significant portions of California (CA), Nevada (NV), Utah (UT), and Colorado (CO), and three Canadian provinces: British Columbia (BC), Alberta (AB), and Saskatchewan (SK).

1,252 areas (Table 1), and covered 8.2% of the total study area. Protected areas ranged in size from 10.05 km^2 to 11,223.19 km^2.

We used both historical and projected future climate data sets to assess potential changes in climate. The historical climate data were 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 (Table 2) 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 with slightly less precipitation, but with intense, warm summers (Hadley CM3). The A2 emission scenario projects a mid-high level of future greenhouse-gas emissions. Baseline and future vegetation were represented by biomes mapped to the 30-second $\times$ 30-second grid (Rehfeldt et al. 2012). We used two future projections of biome distributions that corresponded with the two GCMs run for the A2 emission scenario.

We projected changes in habitat suitability for 366 terrestrial animal species, including 12 amphibians, 237 birds, and 117 mammals. To make these projections, we drew on existing bioclimatic niche models built using digital range maps for mammals (Patterson et al. 2003), birds (Ridgely et al. 2003), and amphibians (IUCN 2012). The digital ranges were mapped to a 50-km $\times$ 50-km resolution grid (Lawler et al. 2009). For the birds in our study, we included only species with a breeding and/or year-around range in the study region. The models were built using the Random Forests algorithm (Breiman 2001) to correlate known species range locations with the 23 bioclimatic variables. The models were built using 80% of the presences and

Table 1. Protected areas (PA) included in the study.

Protected area designation	Count	Area (sq. km.)
Biosphere Reserve	1	16.15
Botanical Reserve	4	128.59
Class A Park	190	76,419.35
Conservancy	96	18,542.50
Ecological Reserve	20	922.63
Habitat Protection Area	6	134.43
Historical Area	1	16.70
LUD: Land Use Designation II	17	1,456.73
Migratory Bird Sanctuary	7	546.42
National Monument	25	14,976.42
National Outstanding Natural Area	6	159.04
National Park (USA)	28	26,596.78
National Park of Canada	28	29,335.86
National Wildlife Area	5	529.76
National Wildlife Refuge	73	12,053.89
Natural Area	8	238.25
Natural Environment Provincial Park	2	183.40
Nature Conservancy Fee Land	5	176.68
Non-Wilderness Monument	1	594.43
Old Growth Habitat	104	3,546.58
Protected Area	27	2,497.82
Provincial Area	3	67.36
Provinical Park	33	1,956.58
Recreation Area	3	177.47
Research Natural Area	62	1,621.97
Scenic Area	2	53.65
Special Interest Area	12	613.26
State Habitat Area	3	86.01
State Park	12	453.03
State Wilderness Area	4	90.32
State Wildlife Management Area	142	4,737.89
Wilderness Area	259	97,137.63
Wilderness Park	1	4,601.08
Wildland Provincial Park	53	9,440.96
Wildlife Management Area	6	1,521.17
Wildlife Preserve	3	68.64

absences for each species. The remaining 20% of the observations were used to test the predictive accuracy of the models. We used only species for which their models correctly predicted at least 80% of the presences and at least 90% of the absences in the test data set. 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 unsuitable.

Climate change

We calculated the magnitude of projected changes in climate using a variation of the standard Euclidean distance (SED) equation described by Williams et al. (2007). Based on previous studies examining climate change hot spots (Diffenbaugh et al. 2008), we selected eight climatic variables: mean annual temperature and mean annual precipitation for the winter, spring, summer, and autumn quarters, averaged over the baseline (1961–1990) and future (2070–2099) 30-year time periods. Each of these climatic variables was normalized, then used in the following equation to calculate the SED values per grid cell:

$$SED = \sqrt{\sum\nolimits_{i}^{8} (x_i - y_i)^2}$$

where *SED* represents the summed standard Euclidean distance, x_i equals the historical value for climate variable i, and y_i equals the projected future value for climate variable i. The calculation was performed using climate variables derived from both of the GCMs used in this study, resulting in two standard Euclidean distance data sets. Finally, the mean SED values were determined for each protected area, for each GCM projection, by calculating the average SED for all grid cells in each protected area.

Vegetation change

Vegetation change was examined by mapping changes in biome types on a cell-by-cell basis, as well as by calculating a biome turnover rate for each protected area. To illustrate broad spatial patterns of vegetation change occurring in the study area, we reclassified biomes mapped by Rehfeldt el al. (2012) to a higher-order classifica-

Table 2. Bioclimatic variables used to develop climate suitability models for the study species.

Bioclimatic variable	Baseline (1961–1990)		CGCM 3.1 (2070–2099)		HADCM3 (2070–2099)	
	Mean	Range	Mean	Range	Mean	Range
Chilling period of days with a mean temperature ≤5°C (days)	180.4	362	139.4	294	140.7	278.4
Growing degree days on a 0°C base (days)	2,432.4	5,996.3	3,450	6,869.5	3,680	7,078.8
Growing degree days on a 5°C base (days)	1,360.3	4,393.3	2,175	5,588.5	2,421	5,865.2
Mean annual temperature (°C)	4.1	25.9	8	25.9	8.5	26.5
Mean temperature of the coldest month (°C)	−11	36.2	−5.2	32.5	−7.3	35.5
Mean temperature of the warmest month (°C)	17.2	24	21.8	25.7	24	26.8
Annual potential evapotranspiration (mm)	676.5	978.9	643.5	849.5	692.8	936.2
Potential evapotranspiration for days with mean temperatures >5°C (mm)	557.3	1,263.5	574.7	1,009.7	624.5	1,072.3
December–February potential evapotranspiration (mm)	31.9	116.2	33.7	102.4	31.8	105.9
Potential evapotranspiration for days with mean temperatures >−4°C (mm)	655.2	1039.5	635.1	886.1	682.3	974.9
June–August potential evapotranspiration (mm)	343.5	384.1	327.8	350.7	359.7	392.2
March–May potential evapotranspiration (mm)	191.2	284	173.2	242.9	182.5	243.7
September–November potential evapotranspiration (mm)	109.9	214.4	108.8	184.4	118.7	210.3
Total precipitation of the wettest month minus total precipitation of the driest month (mm)	121.6	721.2	120.2	790.7	118.3	846.6
Total annual precipitation (mm)	666.6	4,863.1	793.5	6,004.1	715	5,512.5
December–February total precipitation (mm)	188.6	1,580	234.3	1,905	219.2	1,752
Total precipitation of the driest month (mm)	12.6	134.3	20.9	171.6	16.2	146.4
June–August total precipitation (mm)	158.9	688.2	168.2	726.8	151	680.2
March–May total precipitation (mm)	146.2	970.1	182	1,295.9	155.1	1,077.7
September–October total precipitation (mm)	172.9	1,852.9	208.9	2,223.9	189.5	2,225.5
Total precipitation of the wettest month (mm)	134.2	829.4	141.1	893.2	134.5	986.2
Total annual snow water equivalent (mm)	209.7	2,878	163	2,452	181.2	2,417
Mean temperature of the warmest month minus mean temperature of the coldest month (°C)	28.23	36	26.95	31.8	31.3	34.6

tion within the Brown et al. (1998) vegetation classification system (the "third-order formations"). We then produced a binary map depicting where these basic vegetation types were projected to change and conversely remain the same as the climate changes.

We calculated the biome turnover rate for each protected area by tallying the number of biomes currently represented in the protected area that were not projected to be in the area in the future (contraction), the number of biomes that were not currently in the protected area but were projected to move into the protected area (expansion), and the total number of biomes that were projected to be represented in the area in the current and future time periods (stable). We included these three metrics in a measure of turnover using the following equation:

$$BTR = \frac{(e + c)}{(e + c + s)}$$

where BTR represents the biome turnover rate, e is the total number of biome expansions within each area, c is the total number of biome contractions, and s is the total number of stable biomes.

Species turnover

Similarly, we calculated species turnover based on the number of species for which our models projected a loss of representation in a cell (contraction, c), a gain of representation in a cell (expansion, e), and sustained representation in a cell (stable, s). We calculated species turnover rate (STR) on a cell-by-cell basis as:

$$STR = \sum \frac{(e + c)}{(e + c + s)}.$$

This calculation produced species suitability turnover values for each grid cell in the study area. Although individual species dispersal rates will ultimately determine how effectively species can emigrate from unsuitable climates to colonize new suitable climate spaces, we did not include dispersal as a factor in the species turnover rate—our calculations are based only on a change in

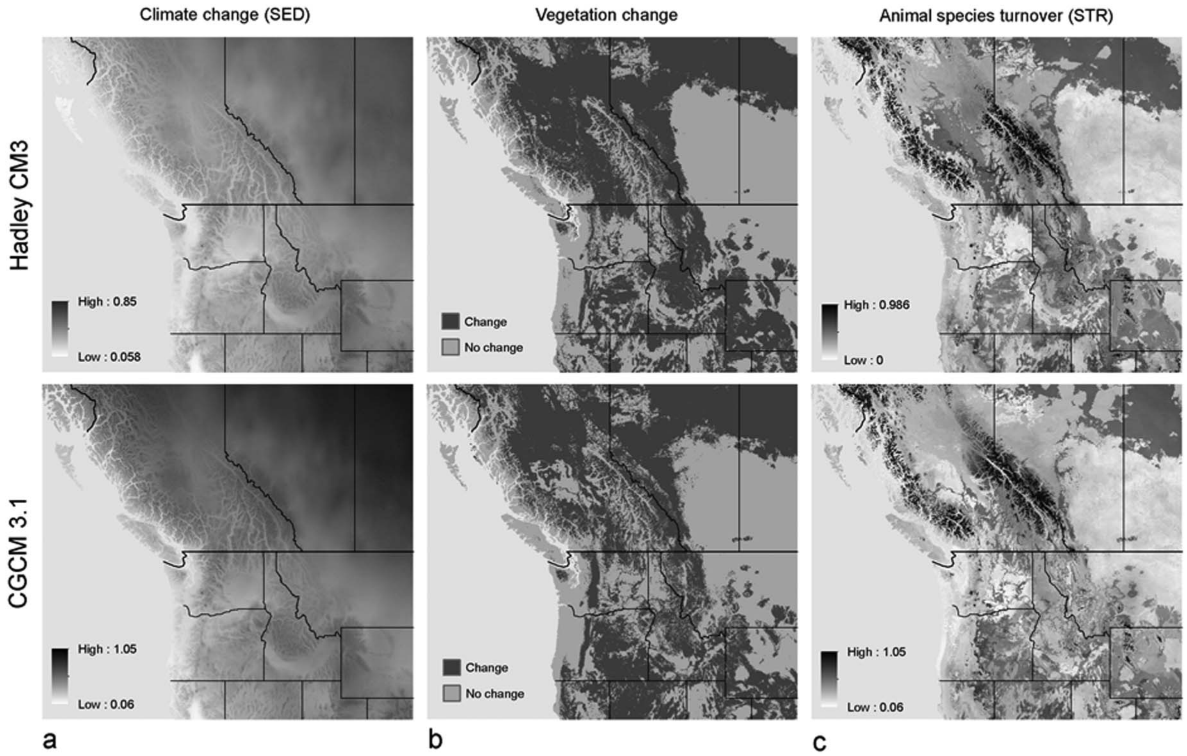

Fig. 2. Climate change represented by the standard Euclidean distance (SED) for 8 temperature and precipitation variables (a), vegetation change (b), and animal species suitability turnover rate (STR) (c) for the study area.

suitability, and thus do not directly represent projected presence or absence of a species.

To calculate species turnover for each protected area, we used the same equation, but defined expansion, contraction, and stability in slightly different ways. We defined contraction (c) as the number of species for which some portion of the protected areas was projected to be currently suitable but for which none of the area in the future was projected to be suitable. Expansion (e) was the number of species for which the protected area was projected to become newly suitable. And, stability (s) was the number of species with at least one suitable grid cell in the area for both the current and future time periods.

To better understand some of the patterns of climate change, vegetation shifts, and animal species turnover rates, we also examined correlations between each of these factors and mean elevation, maximum elevation, latitude, longitude, and protected area size. Before conducting the correlation analyses, we transformed species turnover with a square-root transformation and protected area size by taking the inverse log to address skewed distributions.

Finally, we simultaneously mapped all three impact measures to highlight the protected areas that will potentially experience the most (and least) change across all three dimensions. We classified protected areas as being more or less cumulatively impacted based on how many of the three metrics had values in the highest or the lowest quartiles of their respective distributions.

Results

Both future climate projections forecast significant changes for much of the region and both produced spatial patterns in the variation in climate change (Fig. 2a). In general, the magnitude of climate change is projected to gradually increase along a longitudinal gradient from west to east, with the lowest values concentrated along the Pacific coast, and the highest values

Table 3. Biome types mapped by Rehfeldt et al. (2012), and originally developed by Brown et al. (1998), which intersect the study area in either the baseline or future climate scenarios. Area values are given in square kilometers.

Biome name	Baseline (1961–1990)	CGCM 3.1 (2070–2099)	HADCM3 (2070-2099)
Adirondack-Appalachian Subalpine & Tundra	0	651	9
Alaskan-Alpine Tundra	90,280	11,219	4,396
Alaska-Yukon Subarctic Conifer Forest	620	716	7,742
California Chaparral	7,153	6,174	5,940
California Coastalscrub	0	4,984	2,340
California Evergreen Forest and Woodland	18,397	54,893	44,741
California Valley Grassland	7,653	1,078	637
Canadian Taiga	575,472	32,854	96,236
Cascade-Sierran Montane Conifer Forest	113,083	135,417	181,607
Cascade-Sierran Subalpine Conifer Forest	67,900	11,782	14,535
Chihuahuan Desertscrub	0	7	817
Cloud Forest	0	1,102	0
Great Basin Conifer Woodland	171,971	109,032	89,659
Great Basin Desertscrub	220,060	292,858	456,606
Great Basin Montane Scrub	61,567	74,350	207,079
Great Basin Shrub-Grassland	381,114	200,038	221,871
Interior Cedar-Hemlock Conifer Forest	114,347	251,734	215,942
Interior Chaparral	0	6,918	187
Madrean Montane Conifer Forest	0	18	0
Mohave Desertscrub	249	231,847	28,980
Northeastern Deciduous Forest	0	263,418	250,714
Northern Tundra	31	0	0
Oregonian Coastal Conifer Forest	75,121	90,715	23,724
Oregonian Deciduous and Evergreen Forests	31,378	40,798	11,200
Plains Grassland	405,584	754,843	922,011
Rocky Mountain Montane Conifer Forest	256,517	262,963	137,835
Rocky Mountain Subalpine Conifer Forest	407,624	30,271	108,007
Semidesert Grassland	0	5,999	19,266
Semi-evergreen Forest	0	19	0
Sitka Coastal Conifer Forest	186,345	378,588	206,127
Sonoran Desertscrub	0	482	2
Southeastern Deciduous and Evergreen Forests	0	386	0
Tamaulipan Thornscrub	0	955	18
Western Alpine Tundra	73,437	423	150

in the northeastern portion of the study area. Additionally, projected changes tend to be greater at higher elevations. The average magnitude of climate change (SED) for the study area was 0.56, ranging from 0.06 to 1.05 (SD = 0.19), based on the CGCM3.1 projection, which is higher than the average value of 0.45, ranging from 0.06 to 0.85 (SD = 0.14), resulting from the Hadley CM3 projection. The average magnitude of change projected to occur within the study's protected area network is generally lower than the average for the study area, at 0.47 with a range of 0.06 to 0.93 (SD = 0.15) based on the CGCM 3.1 model, and an average of 0.37 with a range of 0.06 to 0.71 (SD = 0.16) for the Hadley CM3 projection.

Under historical climatic conditions, the study area was represented by 22 biomes. Under projected future climatic conditions from the CGCM 3.1 and Hadley CM3 models, the region was projected to host 33 and 28 biomes, respectively (Table 3). The projections from both of the GCMs resulted in little to no change in biome distribution along the coastal lowlands and mountains and the Great Plains, whereas both resulted in shifts in biomes at high elevations, throughout the mountains in the continental interior, and along the southernmost edge of the taiga forests (Fig. 2b). Projected biome turnover rates in protected areas follow these general patterns—high biome turnover is projected along the entire Rocky Mountain range and low biome turnover is limited to the northwestern region of the study area and along the B.C. coast and Coastal Mountains (Fig. 3b). The average biome turnover rate projected to occur within the study's protected area network is 0.57, ranging from 0 to 1 (SD = 0.38) based on the CGCM 3.1 model, and average turnover rate of 0.5 with a range of 0 to 1 (SD = 0.4) for the

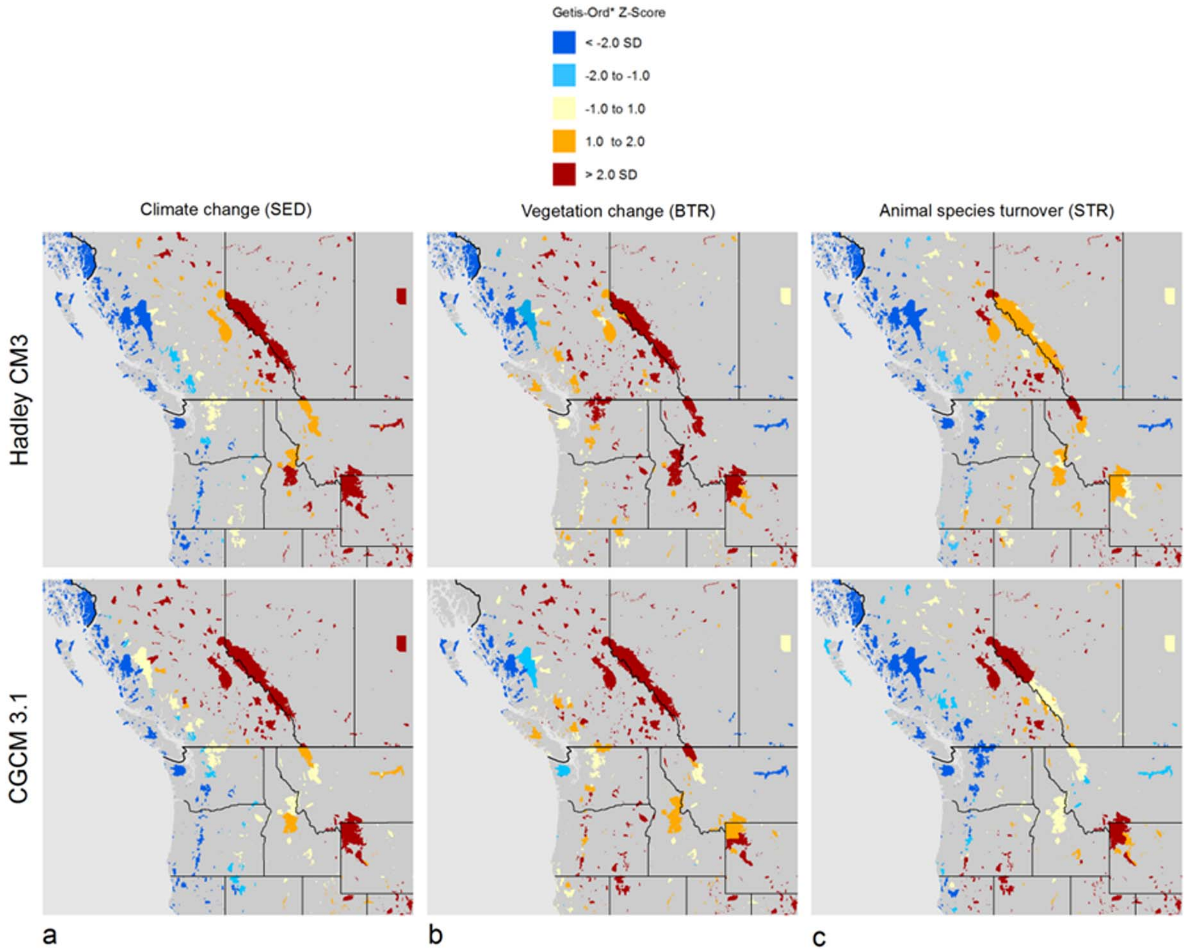

Fig. 3. Hot and cold spots of climate change as standard Euclidean distance for 8 temperature and precipitation variables (a), vegetation change as biome turnover rate (b), animal species suitability turnover rate (c), summarized by protected areas. Hot and cold spots were determined using the Getis-Ord Gi* statistic, in which a z-score is calculated to indicate statistically significant clusters of high or low values.

Hadley CM3 projection.

On average, across all 1-km^2 grid cells, the projected species turnover rate for the study area was 31% (SD = 20%) for the CGCM 3.1 projection, and 34% (SD = 21%) for the Hadley CM3 projection (Fig. 2c). Areas projected to have higher than average STR values are clustered along the Northern and Southern regions of the Rocky Mountains and throughout the higher elevations of the Great Basin, whereas areas with lower than average STR values are found along the West Coast, the Cascade and Coastal Mountains, lower elevations in the Great Basin, and large contiguous areas of the Great Plains region (Fig. 3c). Protected areas were found to have lower species turnover rates (measured as averaged turnover across the grid cells in the areas) than the region as a whole. Species turnover as calculated for each protected area ranged from 1.6% to 92% with an average of 22% (SD = 12%) for the CGCM 3.1 projection, and 25% (SD = 14%) with a range of 0.02% to 92% for the Hadley CM3 projections (Fig. 4). From here on, results refer only to the species and biome turnover rates calculated for the protected area network.

Of the three measures of projected change in the protected areas, only species turnover and biome turnover were at least moderately correlated ($r = 0.61$, $p < 0.01$; Fig. 4a). However, all three impact measures were correlated with

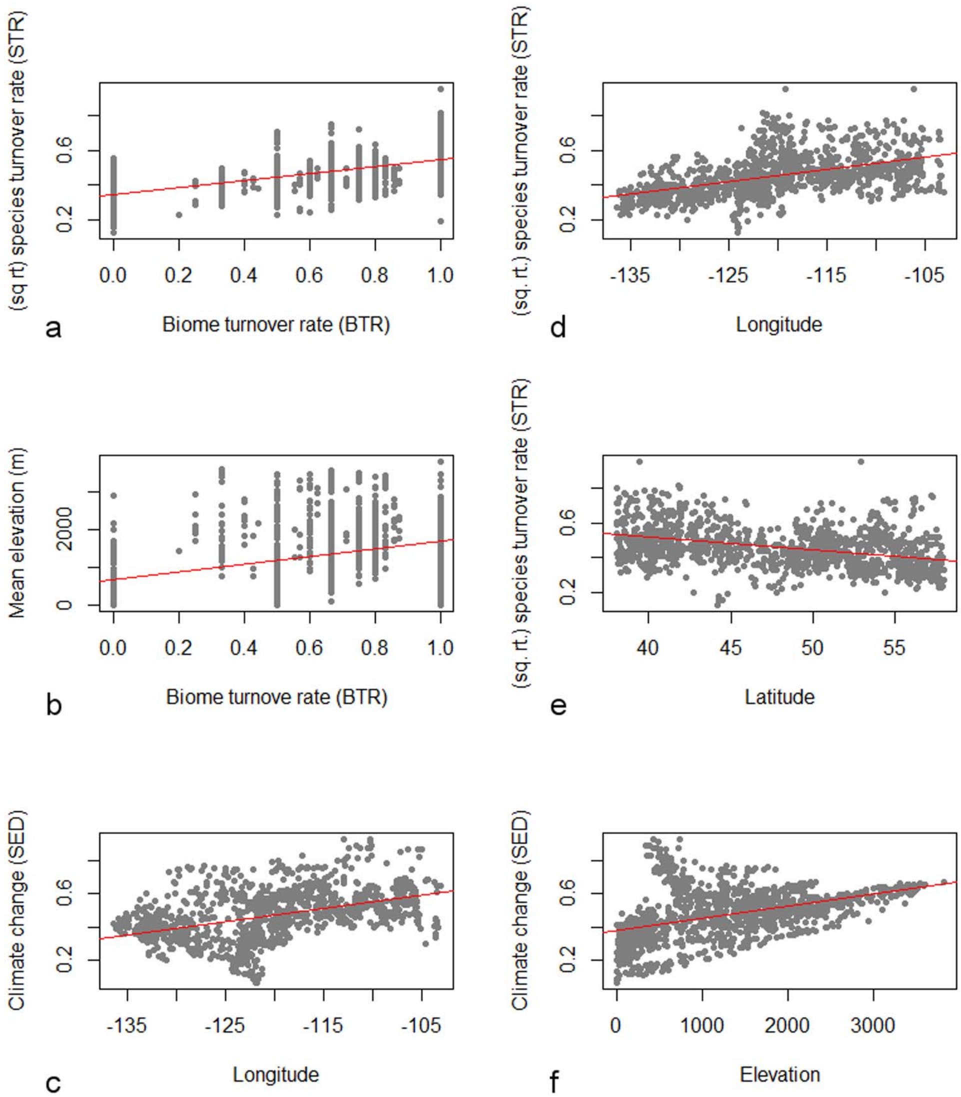

Fig. 4. Relationships between species turnover rate (STR) and biome turnover rate (BTR) (a), BTR and mean elevation (b), climate change represented by standard Euclidean distance (SED) and longitude (c), STR and longitude (d), and STR and latitude (e). Each dot in the scatterplot represents one protected area record. Plots are from the CGCM 3.1 model projections.

elevation, latitude, or longitude. For example, biome turnover was positively correlated with elevation ($r = 0.41$, $p < 0.01$; Fig. 4b). Both the magnitude of climate change (SED) and species turnover rates were positively correlated with longitude—increasing to the east ($r = 0.64$, $p < 0.01$; Fig. 4c; $r = 0.54$, $p < 0.01$; Fig. 4d). Species turnover was only moderately correlated with latitude—with lower turnover rates at higher latitudes ($r = -0.42$, $p < 0.01$; Fig. 4e), and the magnitude of climate change was moderately correlated with elevation ($r = 0.42$, $p < 0.01$; Fig. 4f). We found no correlation between species turnover and protected area size, nor between protected area size and the other two impact measures.

Projections from the two climate models resulted in 5% (CGCM 3.1) and 7% (Hadley CM3) of the protected areas being simultaneously ranked in the highest quartiles of STR, BTR

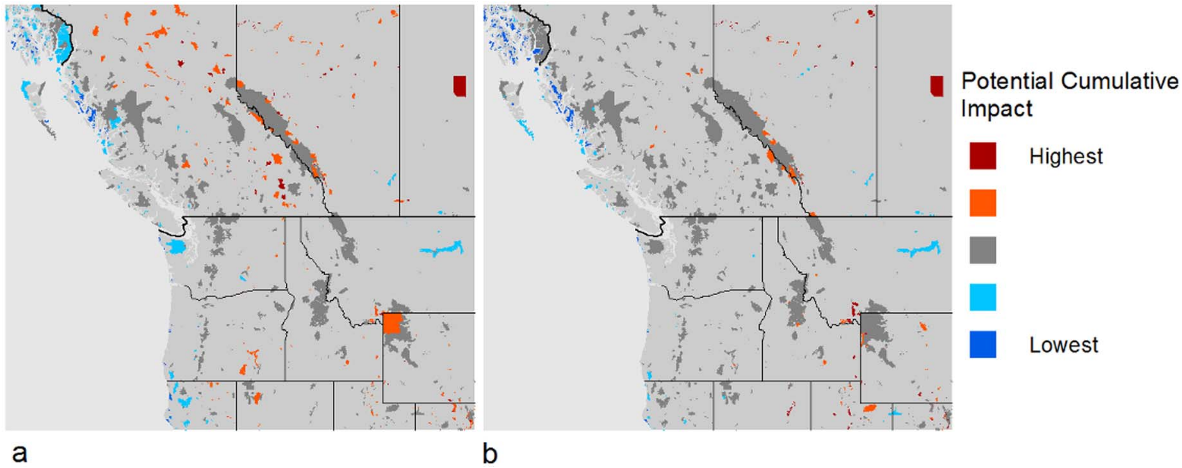

Fig. 5. Map illustrating protected areas with lowest (blue) and highest (red) potential climate change impacts, based on the CGCM 3.1 (a) and Hadley CM3 (b) projections. The protected areas were categorized by quartile for each of the three summarized metrics: species suitability turnover rate (STR), biome turnover rate (BTR), and Euclidean distance for the climate change variables (SED). Protected areas associated with fourth quartiles for all three measures were included in the highest impact category, and areas with values in the first quartile for all three measures were classified as lowest impact. Orange and light blue colors indicate that at least two impact measures were in the highest or lowest quartiles respectively.

and SED, and between 6% (CGCM 3.1) and 13% (Hadley CM3) being simultaneously ranked in the lowest quartile of all three measures. This categorization again indicates that protected areas at higher elevations will likely be more affected by climate change than those at lower elevations. The areas simultaneously ranked highly by all three measures had an average elevation of 1536 m (CGCM 3.1) and 1950 m (Hadley CM3), whereas the group simultaneously ranked in the lowest quartile by the three measures had average elevations of 255 m (CGCM 3.1) and 243 m (Hadley CM3). In addition, less change was forecasted for coastal protected areas than for those in the continental interior, with the majority of high change sites straddling higher elevations along the continental divide (Fig. 5).

Discussion

Although climate change is a global phenomenon, the amount and nature of the change, and its impacts, will vary substantially from region to region (IPCC 2013, 2014). Even within the confines of the North American Pacific Northwest, our results indicate that climate change, shifts in biomes, and animal species turnover will likely vary greatly with longitude and elevation. In addition, we found that some protected areas in the Pacific Northwest are projected to experience large changes in climate but smaller changes in biota or conversely small changes in climate and large changes in biota. All of this variation has important implications for the prioritization of management actions intended to address climate impacts.

Our analyses highlighted several protected areas, such as the Purcell Wilderness Conservancy Provincial Park and Protected Area, which are projected to experience large changes in climate, biomes, and animal species composition. This park is projected to see increased mean temperatures between 3.1° to 3.2°C, and 13% to 23% increases in total annual precipitation. High elevation tundra is projected to disappear throughout the park, and be replaced by expanding low elevation forests and subalpine forests. Subsequently, alpine-dependent species such as the Hoary marmot (*Marmota caligata*) may experience a significant reduction in suitable habitat, eventually being displaced by forest-dependent species such as the Cinereus shrew (*Sorex cinereus*) and Mountain shrew (*Sorex monticolus*). For protected areas such as this one, management efforts will likely need to embrace change to be successful (Stein et al. 2014). Such efforts might include increasing connectivity between the protected area and other areas, incorporating new plant species or seeds from different seed provinces into restoration efforts in the protected area, and in extreme cases—for species at risk of extinction that are unable to move on their own—assisted colonization (Hunter 2007, Hoegh-Guldberg et al. 2008).

Our results highlighted other areas, such as Kitlope Heritage Conservancy Provincial Park, which are likely to see relatively little change in climate, biomes, or animal species. These areas could be considered to be relatively low-risk with respect to climate change and could potentially be managed largely as they are today. By contrast, areas such as Ts'yl-Os Provincial Park, which are projected to see a moderate amount of change in climate and biota, would be candidates for targeted monitoring efforts aimed at specific biome types or species projected to gain or lose climatic suitability over the coming century. These areas would also be reasonable sites for management strategies aimed at building resilience—that is, management activities that will allow current systems and species to persist in the protected area in the face of climate change. These actions might include habitat improvements, and reducing the effects of non-climatic threats such as invasive species, disease, or impacts from recreation, logging, or other human activities.

Perhaps more challenging for managers and planners will be the protected areas that are projected to experience small changes in climate but relatively large changes in biota—or vice versa. Areas such as Lassen Volcanic National Park which are projected to see relatively small changes in climate but large changes in biota, may be difficult to plan for. They may include ecotones and species at the edges of their ranges. In such cases, minor changes in climate may result in large changes in biota. In these protected areas, ecological changes may come as surprises given the relatively slow changes in climate. These are good locations for intensive monitoring and adaptive management experiments because biotic responses to subtle climatic changes will likely be less predictable and managers and ecologists will be able to learn from carefully planned actions.

Finally, areas such as the Charles M. Russell National Wildlife Refuge, which are projected to experience large changes in climate but relatively small changes in biota, may be areas where the current biota will be more resilient to climate change, and management actions can potentially be designed to maintain current species assemblages and ecosystems. However, the mismatch between the magnitude of the climatic change projections and the biotic change projections may also highlight potential shortcomings of the biotic models, used in our analyses. Correlative models such as those used here, merely explore whether future climatic conditions will be similar to the ones occupied by a biome or species today—they do not account for the multiple, complex ways in which climate change could affect a species or ecosystem (Pearson and Dawson 2004, Heikkinen et al. 2006). Thus, protected areas with large projected changes in climate and relatively small projected changes in biota might be areas in which managers and planners will want to identify more nuanced metrics of biotic change (e.g., population trends).

It is worth noting that our projected average species turnover rates (31% and 34%) are generally lower than turnover rates found in related studies. For the mid-high A2 emission scenario, Lawler et al. (2009) estimated average turnover rates of 38% for 2,954 amphibians, birds, and mammals in North and South America. Peterson et al. (2002) modeled changes in distributions for 1,870 species in Mexico, and found maximum species turnover rates of 45%. In Europe, Thuiller et al. (2005) projected future distribution shifts for 1,350 plant species, using the A2 emission scenario with the CGCM2 and Hadley CM3 models, and estimated average species turnover rates between 45% and 55%. These differences are likely due in part to dissimilar methodologies, such as differences in spatial resolution of data, the number and types of study species, or alternative methods for calculating turnover rates. The disparity in turnover rates may also be the result of inherent differences in temperature and precipitation changes projected to occur in Mexico, Europe, the Western Hemisphere, and the Pacific Northwest.

Surprisingly, we found little correlation between species or biome turnover rates and protected area size. Larger areas should be more likely to accommodate projected shifts in biomes and species ranges—allowing species to stay within protected area boundaries more often than smaller reserves would. Although others have come to similar conclusions—e.g., little relationship between extinction rates and reserve size (Parks and Harcourt 2002), or between turnover rates and habitat area (Hinsley et al. 1995)—the lack of correlation between species or biome turnover and protected area size in our study is most likely due to the extremely skewed size distribution of the protected areas in the region. The majority (79%) of the protected areas within the study region cover less than 200 km^2 and less than 1% are greater than 4,000 km^2. Accordingly, this lack of relationship between protected area size and turnover rate may be due to the fact that there are few, if any, reserves large enough to accommodate climate-driven changes in the region. Thus, to be resilient to the effects of climate change, protected areas in the region may need to be considerably larger than they are currently, ideally to encompass a wide range of elevational gradients and biomes. Furthermore, given the amount of movement and turnover projected for some regions, it will be necessary to continue to focus on habitat management both inside and outside of protected areas—as protected areas will likely be necessary, but insufficient in themselves to conserve biodiversity in a changing climate.

Our measure of species turnover is a summation of changes to habitat suitability for a relatively large number of species. By necessity, the species habitat suitability models are a simplification of how species inhabit the landscape. These models are correlative, and do not take into account important limiting factors such a species-specific dispersal rates, biotic interactions, and major stochastic events, nor do they consider evolutionary mechanisms for short-term adaptations (Heikkinen et al. 2006). Thus the habitat suitability models, like all models, have associated uncertainties. Similarly, the projected biome changes (Rehfeldt et al. 2012) are also a necessary simplification of how vegetation will likely change. The models behind these projections are correlative and the caveats about the individual vertebrate species models apply to the biome projections as well. In addition, it is important to note that the biome projections—like the species projections—are in essence, equilibrium projections. That is, they assume that a given biome will exist in a given climate. They do not take into account the time lag that will be necessary for a transition from one biome type to another to occur. Some transitions (e.g., grassland to shrubland or shrubland to woodland) might be relatively rapid, whereas transitions from one forest type with long-lived mature trees that can withstand large climatic fluctuations to another forest type may occur over a longer period of time.

Although projected impacts of climate change are often dire, our results highlight the fact that some protected areas may experience much less change than others. Simply knowing where the greater and lesser climate-driven ecological changes in a landscape may occur gives conservation practitioners and natural resource managers some means for prioritizing their activities and allocating limited funds. Such an understanding also facilitates the development of regional experiments and the design of targeted monitoring programs to better understand and track the impacts of climate change. Knowing exactly how the ecology of a specific area will be altered by a changing climate is an unobtainable goal for most locations, but knowing, with some certainty, what sites will be most and least impacted is essential information for the development of effective climate adaptation and mitigation efforts going forward.

Acknowledgments

We would like to thank Elizabeth Gray and Steve West for their guidance and feedback throughout development of this research. We would also like to thank the members of the Pacific Northwest Climate Change Vulnerability Assessment team, for providing feedback and data resources that were vital to the completion of the project. Finally, we thank the Department of Interior's Northwest Climate Science Center Fellowship Program for funding. We are grateful for additional funding provided by grants from the Northwest Climate Science Center, the National Climate Change and Wildlife Science Center, the National Park Service, and the Wilburforce Foundation.

Literature Cited

Araújo, M. B., D. Alagador, M. Cabeza, D. Nogues-Bravo, and W. Thuiller. 2011. Climate change threatens European conservation areas. Ecology Letters 14:484–492.

Araújo, M., M. Cabeza, W. Thuiller, L. Hannah, and P. H. Williams. 2004. Would climate change drive species out of reserves? An assessment of existing reserve-selection methods. Global Change Biology 10:1618–1626.

Araújo, M., R. G. Pearson, W. Thuiller, and M. Erhard. 2005. Validation of species climate impact models under climate change. Global Change Biology 11:1504–1513.

Breiman, L. 2001. Random Forests. Machine Learning 45:5–32.

Brown, D. E., F. Reichenbacher, and S. E. Franson. 1998. A classification of North American biotic communities. University of Utah Press, Salt Lake City, Utah, USA.

Chen, I. C., J. K. Hill, R. Ohlemuller, D. B. Roy, and C. D. Thomas. 2011. Rapid range shifts of species associated with high levels of climate warming. Science 333:1024–1026.

Diffenbaugh, N. S., F. Giorgi, and J. S. Pal. 2008. Climate change hotspots in the United States. Geophysical Research Letters 35:L16709.

Dobrowski, S. Z., J. Abatzoglou, A. K. Swanson, J. A. Greenberg, A. R. Mynsberge, Z. A. Holden, and M. K. Schwartz. 2013. The climate velocity of the contiguous United States during the 20th century. Global Change Biology 19:241–251.

Dudley, N., editor. 2008. Guidelines for applying protected area management categories. IUCN, Gland, Switzerland.

Flato, G. M., G. J. Boer, W. G. Lee, N. A. McFarlane, D. Ramsden, M. C. Reader, and A. J. Weaver. 2000. The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate. Climate Dynamics 16:451–467.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood. 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics 16:147–168.

Hannah, L., G. Midgley, S. Andelman, M. Araújo, G. Hughes, E. Martinez-Meyer, R. Pearson, and P. Williams. 2007. Protected area needs in a changing climate. Frontiers in Ecology and the Environment 5:131–138.

Hannah, L., G. Midgley, G. Hughes, and B. Bomhard. 2005. The view from the cape. Extinction risk, protected areas, and climate change. BioScience 55:231–242.

Heikkinen, R. K., M. Luoto, M. B. Araújo, R. Virkkala, W. Thuiller, and T. Martin. 2006. Methods and uncertainties in bioclimatic envelope modelling under climate change. Progress in Physical Geography 6:1–27.

Hinsley, S. A., P. E. Bellamy, and I. Newton. 1995. Bird species turnover and stochastic extinction in woodland fragments. Ecography 18:41–50.

Hoegh-Guldberg, O., L. Hughes, S. McIntyre, D. B. Lindenmayer, C. Parmesan, H. P. Possingham, and C. D. Thomas. 2008. Assisted colonization and rapid climate change. Science 321:345–346.

Hunter, M. L. 2007. Climate change and moving species: furthering the debate on assisted colonization. Conservation Biology 21:1356–1358.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, New York, USA.

IPCC. 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

IUCN. 2012. Red List Spatial Data. http://www.iucnredlist.org/technical-documents/spatial-data

IUCN and UNEP. 2010. The World Database on Protected Areas (WDPA). UNEP-WCMC, Cambridge, UK.

Lawler, J., S. Shafer, D. White, P. Kareiva, E. P. Maurer, A. R. Blaustein, and P. J. Bartlein. 2009. Projected climate-induced faunal change in the Western Hemisphere. Ecology 90:588–597.

Loarie, S. R., P. B. Duffy, H. Hamilton, G. P. Asner, C. B. Field, and D. D. Ackerly. 2009. The velocity of climate change. Nature 462:1052–1055.

Mitchell, T. D., and P. D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25:693–712.

NatureServe. 2013. NatureServe Explorer: An online encyclopedia of life. NatureServe, Arlington, Virginia, USA. http://explorer.natureserve.org/

New, M., D. Lister, M. Hulme, and I. Makin. 2002. A high-resolution data set of surface climate over global land areas. Climate Research 21:1–25.

Parks, S. A., and A. H. Harcourt. 2002. Reserve size, local human density, and mammalian extinctions in U.S. protected areas. Conservation Biology 16:800–808.

Patterson, B. D., G. Ceballos, W. Sechrest, M. F. Tognelli, T. Brooks, L. Luna, P. Ortega, I. Salazar, and B. E. Young. 2003. Digital distribution maps of the mammals of the Western Hemisphere. Version 1.0. NatureServe, Arlington, Virginia, USA.

Pearson, R. G., and T. P. Dawson. 2004. Bioclimate envelope models: what they detect and what they hide; response to Hampe (2004). Global Ecology and Biogeography 13:471–473.

Pekin, B. K., and B. C. Pijanowski. 2012. Global land use intensity and the endangerment status of mammal species. Diversity and Distributions 18:909–918.

Peterson, A. T., M. A. Ortega-Huerta, J. Bartley, V. Sánchez-Cordero, J. Soberón, R. H. Buddemeier, and D. R. B. Stockwell. 2002. Future projections for Mexican faunas under global climate change scenarios. Nature 416:626–9.

Rehfeldt, G. E., N. L. Crookston, C. Sáenz-Romero, and E. M. Campbell. 2012. North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. Ecological Applications 22:119–41.

Ridgely, R. S., T. F. Allnutt, T. Brooks, D. K. McNicol, D. W. Mehlman, B. E. Young, and J. R. Zook. 2003. Digital distribution maps of the birds of the Western Hemisphere. Version 3.0. NatureServe, Arlington, Virginia, USA.

Shafer, C. L. 1999. National park and reserve planning to protect biological diversity: some basic elements. Landscape and Urban Planning 44:123–153.

Shafer, S. L., J. Atkins, B. A. Bancroft, P. J. Bartlein, J. J. Lawler, B. Smith, and C. B. Wilsey. 2011. Projected climate and vegetation changes and potential biotic effects for Fort Benning, Georgia; Fort Hood, Texas; and Fort Irwin, California. SIR-2011-5099. U.S. Geological Survey, U.S. Department of the Interior, Reston, Virginia, USA.

Stein, B. A., P. Glick, N. A. Edelson, and A. Staudt. 2014. Climate-smart conservation: putting adaptation principles into practice. National Wildlife Federation, Washington, D.C., USA.

Thomas, C. D., et al. 2012. Protected areas facilitate species' range expansions. Proceedings of the National Academy of Sciences 109:14063–14068.

Thuiller, W., S. Lavorel, M. B. Araújo, M. T. Sykes, and I. C. Prentice. 2005. Climate change threats to plant diversity in Europe. Proceedings of the National Academy of Sciences USA 102:8245–8250.

Williams, J. W., and S. T. Jackson. 2007. Novel climates, no-analog communities, and ecological surprises. Frontiers in Ecology and the Environment 5:475–482.

Williams, J. W., S. T. Jackson, and J. E. Kutzbach. 2007. Projected distributions of novel and disappearing climates by 2100 AD. Proceedings of the National Academy of Sciences 104:5738–5742.