Santa Clara University
Scholar Commons

Civil Engineering

School of Engineering

3-2009

Projected climate-induced faunal change in the western hemisphere

Joshua J. Lawler

Sarah L. Shafer

Denis White

Peter Kareiva

Edwin P. Maurer
Santa Clara University, emaurer@scu.edu

See next page for additional authors

Follow this and additional works at: https://scholarcommons.scu.edu/ceng

Part of the Civil and Environmental Engineering Commons

Recommended Citation

Authors

Joshua J. Lawler, Sarah L. Shafer, Denis White, Peter Kareiva, Edwin P. Maurer, Andrew R. Blaustein, and Patrick J. Bartlein

Projected climate-induced faunal change in the Western Hemisphere

Joshua J. Lawler,[1,7] Sarah L. Shafer,[2] Denis White,[3] Peter Kareiva,[4] Edwin P. Maurer,[5] Andrew R. Blaustein,[1] and Patrick J. Bartlein[6]

[1]*Department of Zoology, Oregon State University, Corvallis, Oregon 97331 USA*
[2]*U.S. Geological Survey, Corvallis, Oregon 97331 USA*
[3]*U.S. Environmental Protection Agency, Corvallis, Oregon 97333 USA*
[4]*The Nature Conservancy, Seattle, Washington 98105 USA*
[5]*Civil Engineering Department, Santa Clara University, Santa Clara, California 95053 USA*
[6]*Department of Geography, University of Oregon, Eugene, Oregon 97403 USA*

Abstract. Climate change is predicted to be one of the greatest drivers of ecological change in the coming century. Increases in temperature over the last century have clearly been linked to shifts in species distributions. Given the magnitude of projected future climatic changes, we can expect even larger range shifts in the coming century. These changes will, in turn, alter ecological communities and the functioning of ecosystems. Despite the seriousness of predicted climate change, the uncertainty in climate-change projections makes it difficult for conservation managers and planners to proactively respond to climate stresses. To address one aspect of this uncertainty, we identified predictions of faunal change for which a high level of consensus was exhibited by different climate models. Specifically, we assessed the potential effects of 30 coupled atmosphere–ocean general circulation model (AOGCM) future-climate simulations on the geographic ranges of 2954 species of birds, mammals, and amphibians in the Western Hemisphere. Eighty percent of the climate projections based on a relatively low greenhouse-gas emissions scenario result in the local loss of at least 10% of the vertebrate fauna over much of North and South America. The largest changes in fauna are predicted for the tundra, Central America, and the Andes Mountains where, assuming no dispersal constraints, specific areas are likely to experience over 90% turnover, so that faunal distributions in the future will bear little resemblance to those of today.

Key words: amphibians; birds; climate change; climate envelope models; future projections; mammals; range shifts, species distributions.

Introduction

Recent climatic changes have already caused shifts in species distributions (Parmesan 2006). In general, species have been found to be moving their ranges poleward in latitude and upward in elevation at rates that are consistent with recent temperature increases. Because future changes in climate are projected to be even greater than those of the last century (IPCC 2007*a*), they will likely produce even larger range shifts (Thomas et al. 2004, Thuiller et al. 2005). In many instances, the impacts of these range shifts will go far beyond the mere addition or subtraction of a species to or from a system. Some range shifts will have cascading effects on community structure and the functioning of ecosystems (Lovejoy and Hannah 2005).

A number of studies have projected range shifts for plants and animals in response to potential climatic changes. Projections have been made for plants and animals in Europe (Bakkenes et al. 2002, Berry et al.

2002, Thuiller et al. 2005, Araújo et al. 2006), Africa (Midgley et al. 2002, 2003, Thuiller et al. 2006), and Australia (Williams et al. 2003, Meynecke 2004). In the Western Hemisphere, projections have been made for animals in Mexico (Peterson et al. 2002), plants in Brazil (Siqueira and Peterson 2003), and plants in the United States (Iverson and Prasad 2001, Shafer et al. 2001). In general, these studies conclude that many species are likely to experience relatively large changes in their distributions over the next century.

Most studies that project climate-induced shifts in species ranges at continental scales use bioclimatic models. The bioclimatic modeling approach involves building a statistical or machine-learning based model that relates the current distribution of a species to current climate and then uses this relationship to project a potential future range based on future climate projections (Pearson and Dawson 2003). The approach has the advantage of requiring relatively little data on the specific biology of a given species and thus models can be built for large numbers of species and used over large geographic areas. Tests of bioclimatic models using historic data indicate that these models can accurately capture shifts in species distributions (Araújo et al. 2005).

Bioclimatic models provide a useful first approximation of how the biota of a region may respond to climate change. However, they have their limitations (Pearson and Dawson 2003). The approach does not directly model biotic interactions, dispersal, or evolution. It also assumes that the climate variables used in the models are adequate surrogates for the factors that determine a species' range, which may not be the case for some species. Furthermore, the predictions of the models are difficult to validate. Ideally, bioclimatic models should be tested with completely independent data sets (Araújo et al. 2005). In the absence of these data, estimates of model accuracy from semi-independent model-validation approaches can approximate validation estimates from more independent data sources, particularly for models that more accurately predict semi-independent data sets (Araújo et al. 2005).

Despite these limitations, bioclimatic models can play a significant role in developing our understanding of the potential future effects of climate change. Bioclimatic models should be seen as providing base-line estimates of the magnitude and the distribution of climate-induced changes in biota and not as accurate predictors of the future distributions of individual species (Pearson and Dawson 2004). Although more complex process-based models have been built to project climate-induced shifts in vegetation types or biomes, these models also have limitations and relatively large associated uncertainties (Cramer et al. 2001, Bachelet et al. 2003). The lack of accurate data on the biology of all but the most well-studied species makes building accurate process-based models for more than a few vertebrate species unrealistic. Even with accurate biological data, there is no guarantee that these process-based models would provide more accurate future projections (Robertson et al. 2003).

Range-shift predictions have typically been based on no more than seven climate-change projections (Thuiller et al. 2005). There are, however, many credible projections of future climate, including more than 50 produced for the Intergovernmental Panel on Climate Change Fourth Assessment Report initiative (Meehl et al. 2007). These different projections give different estimates of future climatic changes. Impact assessments based on a single, or even a few climate-change projections may fail to capture the range of potential future outcomes and hence provide misleading results. Evaluations of the potential ecological effects of future climate change must take the inherent uncertainty in these climate projections into account.

Previous range-shift projections have also been limited by uncertainties in modeling approaches and overly simplistic estimates of extinction rates (Harte et al. 2004, Thuiller et al. 2004). Here, we use a consensus-based bioclimatic modeling approach that reduces model uncertainties to assess the potential effects of 30 different future climate simulations on the ranges of 1818 bird, 723 mammal, and 413 amphibian species in the Western Hemisphere. Instead of assessing extinction rates, our approach simply asks whether climatic conditions are predicted to shift so much that a species will not likely be found in a particular location (defined as a particular 50×50 km grid cell) in the future and whether new areas with suitable climatic conditions will emerge.

Materials and Methods

Data

Current geographic ranges were based on digital range maps for 3756 birds (Ridgely et al. 2003), 1561 mammals (Patterson et al. 2003), and 1616 amphibians (data *available online*)[8] in the Western Hemisphere mapped to a 50×50 km resolution equal-area grid. Only the breeding ranges of the birds were used. Range maps depict the extent of species occurrences and as such are scale-dependent abstractions of species distributions (Hurlbert and White 2005). In general, these maps overestimate species' occurrences and can lead to overestimates of species richness (Hurlbert and White 2005, Hurlbert and Jetz 2007). Although the scale dependence of range maps affects patterns of species richness, it should have minimal effects on our estimates of relative faunal change.

We used a 50-km grid to capture the continental-scale climate patterns that influence species distributions. Coarser grids may fail to capture climatic conditions associated with strong elevation gradients in areas of topographic complexity, such as occur across mountain ranges. Furthermore, coarser grids can also result in spurious extrapolations of finer-scale species distribution patterns to larger areas (Rahbek and Graves 2001, Rahbek 2005). The 50-km grid was chosen to strike a balance between the inaccuracies associated with applying a fine-resolution grid to relatively coarse resolution digital-range maps and the inaccuracies incurred by mapping climate at too coarse a resolution. To assess the effect of a grid's spatial resolution on the patterns of faunal change, we projected changes in species ranges at two additional, coarser grid-cell resolutions (100×100 km and 200×200 km).

Modern climate data were created using cloud-cover data from the 30-min CRU CL 1.0 (New et al. 1999) data set (1961–1990 30-year mean), temperature, precipitation, and sunshine data from the 10-min CRU CL 2.0 (New et al. 2002) data set (1961–1990 30-year mean), and monthly temperature, precipitation, and cloud-cover data from the 30-min CRU TS 2.1 (Mitchell and Jones 2005) data set (1901–2002). We used a locally weighted lapse-rate-adjusted interpolation method to interpolate the CRU CL 1.0 and 2.0 data sets to the 50-km grid of the Western Hemisphere. We calculated anomalies for each month in the CRU TS 2.1 data set against a 1961–1990 30-year mean climatology created

---

[8] ⟨www.globalamphibians.org⟩

from the CRU TS 2.1 1961 to 1990 monthly data. Temperature anomalies were calculated as differences (each monthly value minus the 1961–1990 30-year mean value for the same month) and precipitation and sunshine anomalies were calculated as ratios (each monthly value divided by the 1961–1990 30-year mean value for the same month). These anomalies were interpolated to the 50-km grid using a geographic-distance-weighted bilinear interpolation method. The temperature, precipitation, and sunshine anomalies were applied to the interpolated CRU CL 2.0 data on the 50-km grid to create a 1901–2002 monthly data set of temperature, precipitation, and sunshine. We calculated a 1961–1990 30-year mean climatology from these data to use as our modern climate data set.

We used 30 climate simulations to project potential future ranges of species for the time period of 2071–2100. The 30 climate simulations consisted of projections from 10 coupled atmosphere–ocean general circulation models (AOGCMs; Appendix A) run under three different greenhouse-gas emissions scenarios (B1, A1B, and A2). These scenarios represent the lower, mid, and mid-high range of the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000). We chose these 30 climate simulations because they cover a broad range of future greenhouse-gas emissions scenarios and they were all produced as part of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3), allowing us to compare results of our analyses among AOGCMs and across the three scenarios. The future projections, along with their corresponding twentieth-century simulations, were obtained from the WCRP CMIP3 multi-model archive (available online).[9]

A 1961–1990 30-year mean climatology was calculated from the monthly data in each future simulation's corresponding 20th-century simulation. For each future climate simulation, monthly anomalies were calculated between each month of the future simulation and the matching month in the simulated 1961–1990 30-year mean data set. Annual temperature anomalies were calculated as differences (future minus present) and precipitation and cloud-cover anomalies were calculated as ratios (future divided by present). These anomalies were interpolated to the Western Hemisphere 50-km grid using geographic-distance-weighted bilinear inter-polation. The anomalies were then applied to the 1961–1990 30-year mean CRU CL 2.0 temperature and precipitation data and the CRU CL 1.0 cloud-cover data to create monthly future climate data for the period 2001–2100. For both the CRU TS 2.1 and simulated future data sets, percent cloud cover data were converted to percent sunshine using local regression relationships between percent cloud cover and percent sunshine in the CRU CL 1.0 and 2.0 data sets.

We calculated 37 bioclimatic variables (Appendix B) from both the modern and future climate data using an approach modified from Cramer and Prentice (1988). These bioclimatic variables represent the biological mechanisms that influence the distributions of a wide range of vertebrate species. We used mean monthly temperature (°C) and sunshine (%), total monthly precipitation (mm), and soil texture data (Global Soil Data Task 2000) to calculate the bioclimatic variables. Modern bioclimatic variables were created using the 1961–1990 30-year mean climate data and future bioclimatic variables were created using the monthly data for 2071–2100 from each of the 30 AOGCM simulations. These monthly bioclimatic data were then averaged for the period 2071–2100 to create 30-year mean data sets for each future simulation. For four of the 30 AOGCM simulations, data were not available for the year 2100 and thus, 29-year means (2071–2099) were calculated for these simulations.

Modeling approach

The modeling approach involved three steps. First, we used bioclimatic models to relate the observed current range of each species to current climate. Next, we used the 30 different future climate projections to generate 30 potential future ranges for the 2954 species for which we were able to build the most accurate bioclimatic models (Appendix C). Finally, we summarized the projected range shifts across all species and climate-change projections.

All models were built with random forest classifiers (Breiman 2001, Cutler et al. 2007). Random forest classifiers are a model-averaging or ensemble-based approach in which multiple classification or regression tree models are built using random subsets of the data and predictor variables. The model predictions are then combined to produce one prediction for each observation. For each species in the study, 100 classification tree models were built. For our Western Hemisphere data set, the random forest approach produced more accurate predictions of species' current ranges than each of five other commonly used approaches (Lawler et al. 2006).

Our approach involved fitting individual models to species' current distributions by treating areas within the extent of the range maps as presences and the areas outside of the current range as absences. As with other correlative bioclimatic models, this approach involves modeling the realized niche (sensu Hutchinson 1957) of a species (Guisan and Thuiller 2005). Thus, the models are based not only on the climatic constraints on species' distributions, but also on any biotic interactions, human land-use effects, historic extirpations, or other constraints on species' fundamental niches that are evident at a coarse spatial resolution. The climatic variables in the models act as proxies, albeit imperfect ones, for many of these other non-climatic factors. The degree to which the models are able to accurately project species distributions in an altered, future climate depends in

---

[9] ⟨http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php⟩

part on whether those proxies or relationships are similar in the future. For some species, with ranges that are strongly determined by climatic constraints or habitat relationships that are clearly dictated by climate, the models will more accurately project range shifts. This is likely to be the case for many species when models are applied at a coarse spatial resolution. In fact, many of the documented shifts in species distributions have been in directions and at rates that correspond directly with climatic changes (Parmesan and Yohe 2003). For species with ranges that tend to be determined largely by interspecific interactions or, more importantly, interspecific interactions that will change with climate change, correlative bioclimatic models will be less accurate at projecting potential range shifts.

We built the models using 80% of each of the presence and absence observations for each species. We then used the remaining 20% of the data to test the models. In our calculations of potential faunal change, we used only those models that correctly predicted at least 80% of the presences and at least 90% of the absences in the test-data sets. This model-selection process produced models that accurately predicted the current distributions for 1818 bird, 723 mammal, and 413 amphibian species (Appendix C).

To summarize the projected range shifts across all species and climate-change scenarios, we used each of the 30 climate-change projections to estimate potential faunal changes for each of the 15 323 50-km grid cells in the Western Hemisphere. As climate changes, species will differ in their ability to track the change and to move into newly created suitable habitat. We calculated potential faunal change on a cell-by-cell basis assuming no dispersal to new areas with suitable climatic conditions and conversely, assuming unlimited dispersal into new suitable areas. The actual responses of species will likely fall between these two extremes. For the assumption of no dispersal, we calculated "species loss" for a cell as the percentage of all modeled species currently occurring in the cell whose predicted future range did not include the cell. Under the assumption of unlimited dispersal, we calculated "species gains" as the number of species potentially moving into a cell as a result of a projected range expansion expressed as a percentage of the current number of species in the cell. We also calculated "species turnover," a composite measure of both potential species losses and gains. Turnover was calculated as the sum of all species in a cell whose predicted future range did not include the cell plus all species not in the cell whose future range did include the cell, expressed as a percentage of the number of species currently occurring in the cell.

We used a probabilistic ensemble-modeling approach to summarize the 10 predictions of faunal change for each greenhouse-gas emissions scenario by taking the 20th percentiles of the distributions of loss, gain, and turnover values for each grid cell. These values were used to identify areas in which 80% (eight out of 10) of the climate projections for each greenhouse-gas emissions scenario predicted large changes in the vertebrate fauna. We further summarized our results for 23 of 24 major ecoregions in the Western Hemisphere (Appendix D). Due to the difficulties inherent in modeling range shifts for island species, we did not summarize predictions for the West Indies ecoregion.

RESULTS

Eighty percent (eight out of 10) of the climate-change projections resulted in an average loss of 11% of species per grid cell across North and South America under the lower B1 greenhouse-gas emissions scenario and at least 17% loss under the mid-high A2 scenario (Fig. 1A, C). Several areas in the Western Hemisphere were consistently projected to experience large losses of the current fauna. Eighty percent of the analyzed climate-change projections predicted at least 20% species loss under the lower B1 emissions scenario, and at least 50% loss under the mid-high A2 scenario as a result of range contractions in parts of Mexico, Central America, and the Andes Mountains (Fig. 1A, C).

Assuming no limitations to dispersal, several areas were projected to gain new species as a result of range expansions (Fig. 1D–F). Proportionally, the largest potential gains were projected for the high northern latitudes and for the central and northern Andes Mountains. For example, 80% of the climate projections resulted in average gains of at least 30% per grid cell in the Tundra ecoregion under the lower B1 greenhouse-gas emissions scenario and at least 57% gains under the mid-high A2 scenario (Appendix E). In the Northern Andes ecoregion, average gains were at least 21% under the lower B1 scenario and at least 27% under the mid-high A2 scenario. The maximum gains in both of these regions were predicted to be well over 100% under both scenarios.

Combining both potential range contractions and range expansions resulted in relatively large estimates of species turnover (Fig. 1G–I). On average, 80% of the climate projections resulted in at least 25% turnover across all of North and South America under the lower B1 scenario and at least 38% turnover under the mid-high A2 scenario. Again, the largest changes were projected for the Arctic tundra, Mexico, Central America, and the Andes. On average, in the Northern Andes ecoregion, turnover was projected to be at least 41% under the lower B1 emissions scenario and at least 49% under the mid-high A2 scenario (Appendix E). At least one grid cell in each of the 23 major ecoregions in North and South America was predicted to experience at least 60% turnover under the lower B1 emissions scenario and cells in 11 of the 23 ecoregions were predicted to experience at least 100% turnover under the mid-high A2 scenario, which means the vertebrate communities in these areas would bear almost no resemblance to today's fauna. Species turnover estimates derived from range shifts projected on both 100×100
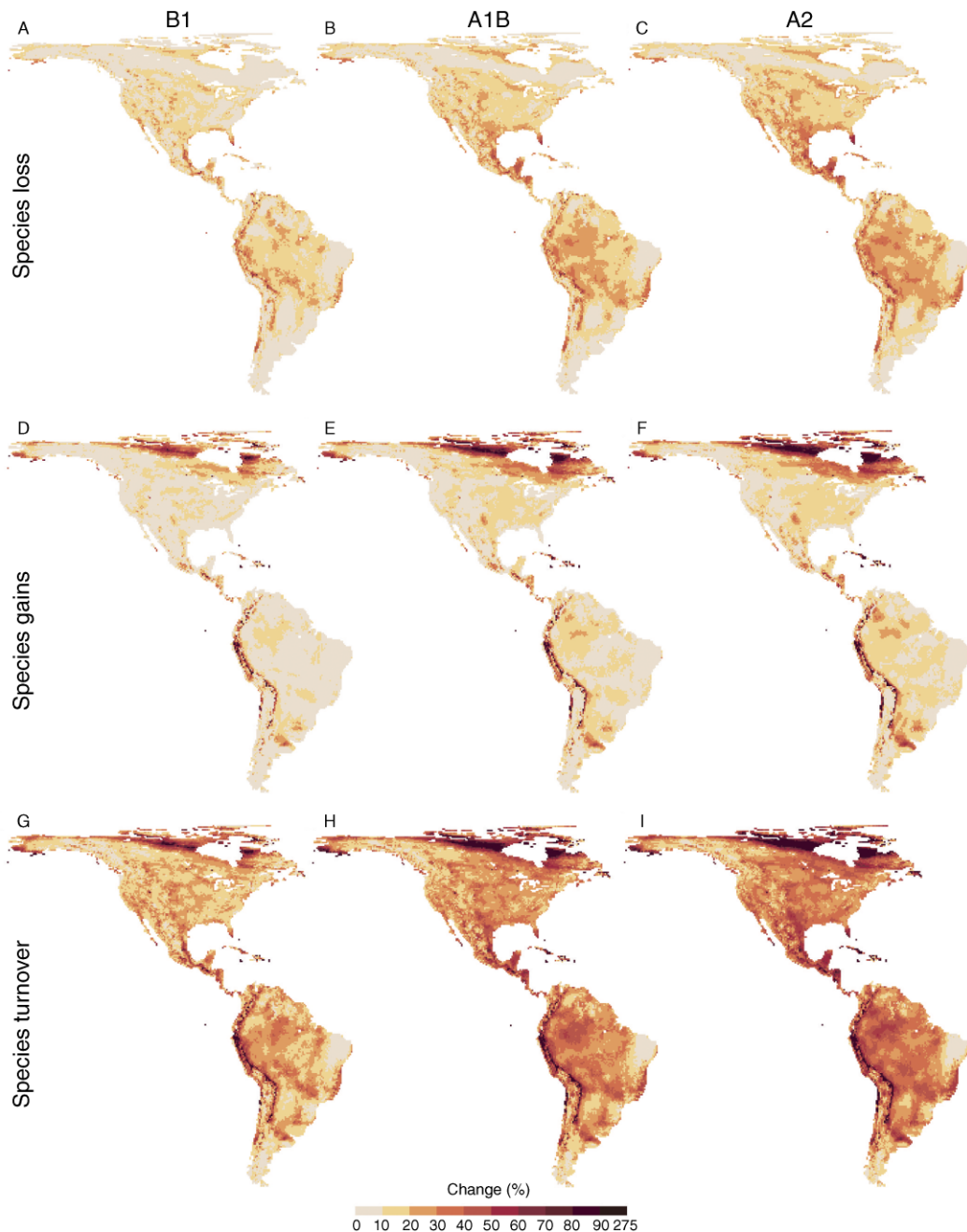
Fig. 1. Consistent predictions of climate-induced (A–C) species range losses, (D–F) expansions, and (G–I) species turnover for lower B1 (A, D, G), mid A1B (B, E, H), and mid-high A2 (C, F, I) greenhouse-gas emissions scenarios. Each map was created using predictions of faunal change (as a percentage) based on 10 different climate-change projections. Species-loss values assume no dispersal of individuals to newly created suitable climatic environments whereas both expansion and turnover values assume that species will be able to move into expanding ranges. Eighty percent of the climate projections (eight of the 10) resulted in losses, gains, and turnover values greater than the values represented in the maps.

km and 200×200 km grids showed very similar patterns to those based on the 50×50 km grid (Fig. 2).

Both the magnitude and the pattern of predicted changes differed across taxonomic groups (Fig. 3). In general, our results indicate that we should expect greater changes in local amphibian fauna than in either mammal or bird fauna. Although all three taxonomic groups were predicted to experience large changes at high northern latitudes, and in the Andes, Mexico, and Central America, amphibians were uniquely predicted to also undergo a high degree of turnover in the central and eastern United States.
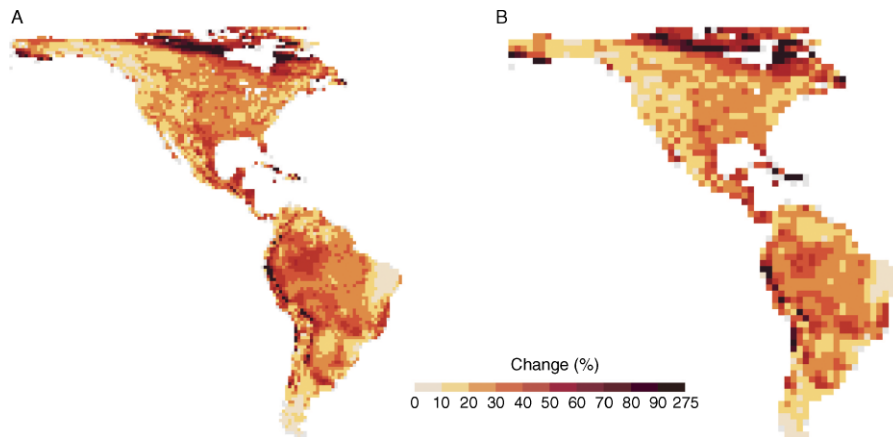
FIG. 2. Consistent predictions of percentage changes in species composition for the mid A1B greenhouse-gas emissions scenarios projected for (A) a 100 × 100 km grid and for (B) a 200 × 200 km grid. Eighty percent (eight of 10) of the future climate projections made for the A1B emissions scenario resulted in greater changes than the values represented in the maps. These maps are directly comparable to Fig. 1H, which depicts similar projections made for a 50 × 50 km grid.

DISCUSSION

Many of the areas predicted to experience large changes in fauna are in mountainous regions where environmental conditions vary significantly over relatively short distances and where the edges of many species' ranges occur. Other areas of high turnover were predicted at ecoregional boundaries such as the southern and western boundaries of the Cerrado of Brazil's central high plains. Several of the areas of high turnover also coincide with identified conservation priority areas. For example, the World Wildlife Fund lists the Atlantic rain forest of South America as one of 200 global conservation priority areas based on its unique and threatened biota (Olson and Dinerstein 1998). Our analyses indicate that the Bahia interior and coastal forests of this region are likely to experience large changes in fauna. The potential for large species losses does not mean that these regions should be neglected by conservation efforts, but rather that climate change may significantly limit efforts directed at retaining specific species in these regions.

It is important to note that our estimates of faunal change are all reported as percentages of the number of species currently at a site. Due to latitudinal trends in species richness, the largest changes in the absolute number of species were predicted for the tropics. Given the potential for overestimating species richness from inaccuracies in the underlying species' range maps, we
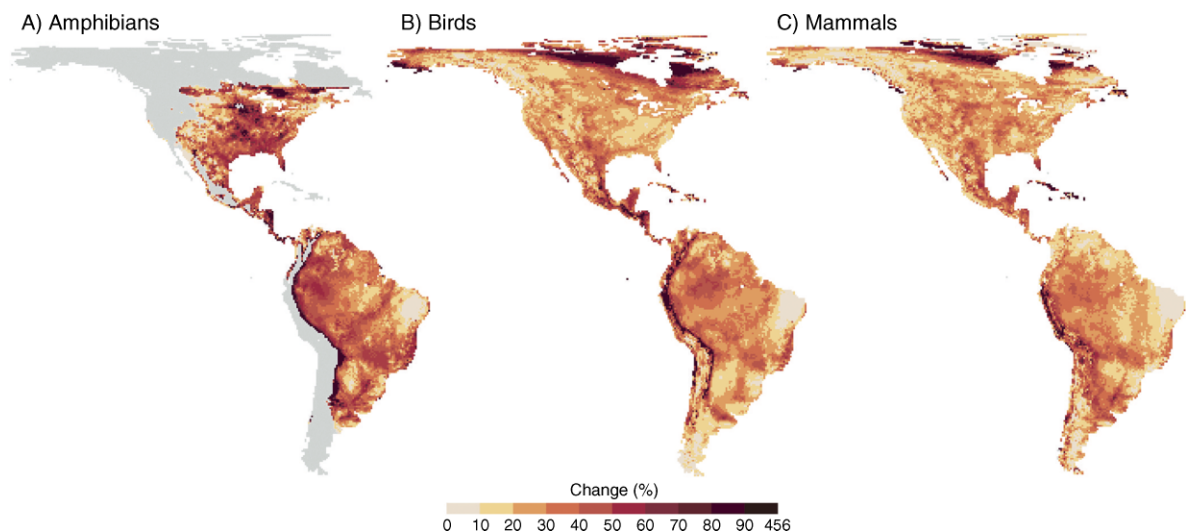

FIG. 3. Consistent predictions of climate-induced species turnover for three major vertebrate taxa. Predictions were made using 10 different climate projections for the A1B mid-range greenhouse-gas emission scenario. Eighty percent (eight of 10) of the climate-change projections resulted in greater species turnover than the values in these maps. For the light gray areas in panel (A), small sample sizes precluded reliable estimates of species turnover.

chose not to report raw species numbers. Nonetheless, even a modest percentage of turnover in the tropics will translate into a large number of species potentially moving in or out of an area.

In addition to regional differences, there are likely to be taxonomic differences in responses to climate change (Parmesan 2006). Previous studies have predicted that amphibians will be more susceptible to climate change than birds or mammals because of their dependence on microhabitats and hydrological regimes, limited dispersal abilities (Blaustein et al. 1994), and susceptibility to diseases that may be influenced by climate change (Pounds et al. 2006). Our models predict substantially larger changes in amphibian fauna than in bird or mammal fauna based solely on potential future range contractions and expansions. In combination, this multitude of projected impacts will likely exacerbate the current declines being observed across many amphibian populations (Stuart et al. 2004).

Our analyses provide a conservative estimate of the future climate-driven changes in biodiversity across North and South America. Because the approach we used does not consider interspecific interactions, it is likely that shifts in the ranges of other species and particularly in the distributions of pathogens (Pounds et al. 2006) will further alter ecological communities, although in some cases, interspecific interactions may buffer the effects of climate change (Wilmers and Getz 2005). Our models also do not account for climate-driven changes in disturbance regimes such as fire or hydrology that may further alter habitat. Nor do our models account for land-use change, which will potentially have even greater impacts than climate change on habitat availability for many species in the coming century (Jetz et al. 2007).

Much of the land in several of the areas highlighted by our analyses has already been converted to agriculture or other human land uses. The Atlantic forest of Brazil and the Amazon basin are just two examples of areas that have undergone, and are projected to undergo, substantial land conversion in the future (Skole and Tucker 1993, Ranta et al. 1998, Nepstad et al. 1999). Although the range maps used in our analyses have been updated and revised by experts, rapid land conversion in these regions may have recently eliminated some species from particular grid cells. Thus, there may be some overestimate of faunal change due to climate change in these areas of rapid land conversion. For those species that have not been recently extirpated, however, the effects of climate change in these areas will likely be even more profound. For many species, these changes will result in the loss of potential future habitat hence limiting potential future distributions. In addition, for many species, fragmented habitats and human land-uses will hinder movement further reducing the ability of species to shift their distributions in response to climate change.

Our projections may also be conservative if future greenhouse-gas emissions surpass the levels specified in the three emissions scenarios used in our analyses. We used the three emissions scenarios on which the IPCC focused their attention for the IPCC Fourth Assessment Report. It is possible, of course, that human activities will result in higher greenhouse-gas concentrations than those resulting from these three scenarios. If that were to be the case, we would expect even larger changes in the distribution of fauna.

Most notably, however, our projections are likely to be conservative because we included in our analyses only those species for which we were able to build models that accurately predicted current ranges. This restriction generally biased us towards excluding species with small and fragmented ranges. These species are likely to be more susceptible to climate-induced range loss and range contraction due to their restrictive habitat requirements. Many of the species with the smallest ranges occur in Central America, the Andes, and in the Atlantic rainforests where our projections also predict major changes in fauna. Other areas such as Mediterranean California, the Mexican Tropical Dry Forests, and the southern Appalachian Mountains of North America were not highlighted by our analyses as areas of projected high faunal change, but may, nonetheless, experience significant changes due to the larger numbers of small-range endemic species they harbor.

As discussed above, bioclimatic models have their limitations. Previous studies have demonstrated that the uncertainties in future range projections attributable to the bioclimatic-modeling process can be even greater than the uncertainties inherent in future climate-change projections (Thuiller 2004). There are several ways to reduce this uncertainty. We chose to use a consensus-based modeling approach that reduced the model errors that are largely responsible for differences in bioclimatic-model predictions. Alternatively, others have suggested model ensembles that combine a wider array of modeling approaches (Thuiller et al. 2005) or combining correlative and mechanistic modeling approaches to produce more realistic models (Botkin et al. 2007). Mechanistic approaches hold great promise for more accurately projecting species future distributions. However, directly modeling the effects of climate change on competitive interactions, predator–prey relationships, and other factors that define species distributions will require much more experimental research in these areas.

There are also a number of limitations associated with the climate simulations that we have used to project future range changes. Future climate simulations include uncertainties that range from differences in how individual AOGCMs are parameterized to stochastic processes in the climate system that are difficult for models to predict (Giorgi 2005). Similarly, the greenhouse-gas emissions scenarios also contain many assumptions about the forces driving emissions, including future population growth rates, economic trends, future

technological advancements, and societal responses to climate change (IPCC 2007b). In our analyses, we used simulations from multiple AOGCMs to include a range of simulated future climate changes and then assessed areas where multiple simulations produced similar projected species range changes. Agreement among AOGCM simulations may be interpreted as a simple measure of model reliability (Giorgi 2005), but it does not necessarily imply increased simulation accuracy.

Our analyses map a geography of projected severe faunal change. Despite the differences among climate projections, our results indicate that even the lower greenhouse-gas emissions scenarios will likely lead to substantial changes in biodiversity. We conclude that as a result of climate change, many areas in the Western Hemisphere will likely experience a significant reorganization of their vertebrate fauna over the coming century. While much discussion of climate impacts has focused on absolute extinction (which is difficult to predict), faunal change alone is a matter of great concern. Change of the magnitude we predict for many regions in the Western Hemisphere, even when it includes the addition of new species to a region, is likely to profoundly alter local ecology and ecosystem functioning. The consequences of such highly altered ecosystems represent one of the great uncertainties climate science needs to begin to address.

LITERATURE CITED

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

Araújo, M. B., W. Thuiller, and R. G. Pearson. 2006. Climate warming and the decline of amphibians and reptiles in Europe. Journal of Biogeography 33:1712–1728.

Bachelet, D., R. P. Neilson, T. Hickler, R. J. Drapek, J. M. Lenihan, M. T. Sykes, B. Smith, S. Sitch, and K. Thonicke. 2003. Simulating past and future dynamics of natural ecosystems in the United States. Global Biogeochemical Cycles 17:1045–1066.

Bakkenes, M., J. R. M. Alkemade, F. Ihle, R. Leemans, and J. B. Latour. 2002. Assessing the effects of forecasted climate change on the diversity and distribution of European higher plants for 2050. Global Change Biology 8:390–407.

Berry, P. M., T. P. Dawson, P. A. Harrison, and R. G. Pearson. 2002. Modelling potential impacts of climate change on the bioclimatic envelope of species in Britain and Ireland. Global Ecology and Biogeography 11:453–462.

Blaustein, A. R., D. B. Wake, and W. P. Sousa. 1994. Global amphibian declines: judging stability, persistence and susceptibility to local and global extinctions. Conservation Biology 8:60–71.

Botkin, D. B., et al. 2007. Forecasting the effects of global warming on biodiversity. BioScience 57:227–236.

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

Cramer, W., et al. 2001. Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models. Global Change Biology 7:357–373.

Cramer, W., and I. C. Prentice. 1988. Simulation of regional soil moisture deficits on a European scale. Norsk Geografisk Tidsskrift 42:149–151.

Cutler, D. R., T. C. Edwards, Jr., K. H. Beard, A. Cutler, K. T. Hess, J. Gibson, and J. J. Lawler. 2007. Random forests for classification in ecology. Ecology 88:2783–2792.

Giorgi, F. 2005. Climate change prediction. Climatic Change 73:239–256.

Global Soil Data Task. 2000. Global soil data products CD-ROM (IGBP-DIS). International Geosphere-Biosphere Programme, Data and Information System, Potsdam, Germany.

Guisan, A., and W. Thuiller. 2005. Predicting species distribution: offering more than simple habitat models. Ecology Letters 8:993–1009.

Harte, J., A. Ostling, J. L. Green, and A. Kinzig. 2004. Biodiversity conservation: climate change and extinction risk. Nature 430. [doi: 10.1038/nature02718]

Hurlbert, A. H., and W. Jetz. 2007. Species richness, hotspots, and the scale dependence of range maps in ecology. Proceedings of the National Academy of Science (USA) 104:13384–13389.

Hurlbert, A. H., and E. P. White. 2005. Disparity between range map- and survey-based analyses of species richness: patterns, processes and implications. Ecology Letters 8:319–327.

Hutchinson, G. E. 1957. Concluding remarks. Population studies: animal ecology and demography. Cold Spring Harbor Symposia on Quantitative Biology 22:415–427.

IPCC. 2007a. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. Cambridge University Press, Cambridge, UK.

IPCC. 2007b. Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. Hanson, editors. Cambridge University Press, Cambridge, UK.

Iverson, L. R., and A. M. Prasad. 2001. Potential changes in tree species richness and forest community types following climate change. Ecosystems 4:186–199.

Jetz, W., D. S. Wilcove, and A. P. Dobson. 2007. Projected impacts of climate and land-use change on the global diversity of birds. PLoS Biology 5:e157.

Lawler, J. J., D. White, R. P. Neilson, and A. R. Blaustein. 2006. Predicting climate-induced range shifts: model differences and model reliability. Global Change Biology 12:1568–1584.

Lovejoy, T. E., and L. Hannah. 2005. Climate change and biodiversity. Yale University Press, New Haven, Connecticut, USA.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Souffer, and K. E. Taylor. 2007. The WCRP CMIP3 multimodel dataset: A new era in climate change research. Bulletin of the American Meteorological Society 88:1383–1394.

Meynecke, J.-O. 2004. Effects of global climate change on geographic distributions of vertebrates in North Queensland. Ecological Modelling 174:347–357.

Midgley, G. F., L. Hannah, D. Millar, M. C. Rutherford, and L. W. Powrie. 2002. Assessing the vulnerability of species richness to anthropogenic climate change in a biodiversity hotspot. Global Ecology and Biogeography 11:445–451.

Midgley, G. F., L. Hannah, D. Millar, W. Thuiller, and A. Booth. 2003. Developing regional and species-level assessments of climate change impacts on biodiversity in the Cape Floristic Region. Biological Conservation 112:87–97.

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.

Nakicenovic, N., et al. 2000. Special report on emissions scenarios. A special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Nepstad, D. C., A. Veríssimo, A. Alencar, C. Nobre, E. Lima, P. Lefebvre, P. Schlesinger, C. Potter, P. Moutinho, E. Mendoza, M. Cochrane, and V. Books, editors. 1999. Large-scale impoverishment of Amazonian forests by logging and fire. Nature 398:505.

New, M., M. Hulme, and P. D. Jones. 1999. Representing twentieth century space-time climate variability. Part 1: development of a 1961–90 mean monthly terrestrial climatology. Journal of Climate 12:829–856.

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.

Olson, D. M., and E. Dinerstein. 1998. The global 200: a representation approach to preserving the Earth's most biologically valuable ecoregions. Conservation Biology 12:502–515.

Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology and Systematics 37:637–669.

Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42.

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. 2003. Predicting the impacts of climate change on the distribution of species: are climate envelope models useful? Global Ecology and Biogeography 12:361–371.

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.

Peterson, A. T., M. A. Ortega-Huerta, J. Bartley, V. Sanchez-Cordero, J. Soberon, R. H. Buddemeier, and D. R. B. Stockwell. 2002. Future projections for Mexican faunas under global climate change scenarios. Nature 416:626–629.

Pounds, A. J., et al. 2006. Widespread amphibian extinctions from epidemic disease driven by global warming. Nature 439: 161–167.

Rahbek, C. 2005. The role of spatial scale and the perception of large-scale species-richness patterns. Ecology Letters 8:224–239.

Rahbek, C., and G. R. Graves. 2001. Multiscale assessment of patterns of avian species richness. Proceedings of the National Academy of Sciences (USA) 98:4534–4539.

Ranta, P., T. Blom, J. Niemela, E. Joensuu, and M. Siitonen. 1998. The fragmented Atlantic rain forest of Brazil: size, shape, and distribution of forest fragments. Biodiversity and Conservation 7:385–403.

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 1.0. NatureServe, Arlington, Virginia, USA.

Robertson, M. P., C. I. Peter, M. H. Villet, and B. S. Ripley. 2003. Comparing models for predicting species' potential distributions: a case study using correlative and mechanistic predictive modelling techniques. Ecological Modelling 164: 153–167.

Shafer, S. L., P. J. Bartlein, and R. S. Thompson. 2001. Potential changes in the distribution of western North America tree and shrub taxa under future climate scenarios. Ecosystems 4:200–215.

Siqueira, M. F., and A. T. Peterson. 2003. Consequences of global climate change for geographic distributions of cerrado tree species. Biota Neotropica 3. ⟨http://www.biotaneotropica.org.br/v3n2/en/fullpaper?bn00803022003+en⟩

Skole, D., and C. Tucker. 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. Science 260:1905–1910.

Stuart, S. N., J. S. Chanson, N. A. Cox, B. E. Young, A. S. L. Rodrigues, D. L. Fischman, and R. W. Waller. 2004. Status and trends of amphibian declines and extinctions worldwide. Science 306:1783–1786.

Thomas, C. D., et al. 2004. Extinction risk from climate change. Nature 427:145–148.

Thuiller, W. 2004. Patterns and uncertainties of species' range shifts under climate change. Global Change Biology 10:2020–2027.

Thuiller, W., M. B. Araújo, R. G. Pearson, R. J. Whittaker, L. Brotons, and S. Lavorel. 2004. Biodiversity conservation: uncertainty in predictions of extinction risk. Nature 430. [doi: 10.1038/nature02716]

Thuiller, W., O. Broennimann, G. Hughes, J. R. M. Alkemade, G. F. Midgley, and F. Corsi. 2006. Vulnerability of African mammals to anthropogenic climate change under conservative land transformation assumptions. Global Change Biology 12:424–440.

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 Science (USA) 102:8245–8250.

Williams, S. E., E. E. Bolitho, and S. Fox. 2003. Climate change in Australian tropical rainforests: an impending environmental catastrophe. Proceedings of the Royal Society B 270: 1887–1892.

Wilmers, C. C., and W. M. Getz. 2005. Gray wolves as climate change buffers in Yellowstone. PLoS Biology 3:e92.

APPENDIX A

Coupled atmosphere–ocean general circulation models (*Ecological Archives* E090-041-A1).

APPENDIX B

Bioclimatic variables (*Ecological Archives* E090-041-A2).

APPENDIX C

Bird, mammal, and amphibian species included in the study (*Ecological Archives* E090-041-A3).

APPENDIX D

Major ecoregions of the Western Hemisphere (*Ecological Archives* E090-041-A4).

APPENDIX E

Table of projected faunal changes for 23 major ecoregions in the Western Hemisphere (*Ecological Archives* E090-041-A5).