ATTACHMENT A

The text that follows herein is an excerpt from the Final Report, entitled "Amphibian and Reptile Climate Change Vulnerability Assessment," by K. Barett, J.C. Maerz and N. P. Nibbelink, 2012). The entire 363 pp. report can be viewed in its entirety at the following links:

MS Word Document:
https://dl.dropbox.com/u/4855847/Amphibian%20and%20Reptile%20Climate%20Change%20Vulnerability%20Assessment_final-report.docx

PDF Document:
https://dl.dropbox.com/u/4855847/Amphibian%20and%20Reptile%20Climate%20Change%20Vulnerability%20Assessment_final-report.pdf

The University of Georgia

Daniel B. Warnell School of Forestry and Natural Resources
Forestry, Wildlife, Water and Soil Resources, Fisheries and Aquaculture, Natural Resource Recreation and Tourism

Amphibian and Reptile Climate Change Vulnerability Assessment

Final Report

Kyle Barrett, John C Maerz, and Nathan P Nibbelink

7/31/2012

This report summarizes the results of (1) a solicitation from eight southeastern states regarding the amphibians of greatest conservation concern to state herpetologists in the face of climate change, (2) spatially-explicit forecasts of shifts in climatic suitability for these species, and (3) spatially-explicit forecasts of shifts in climatic suitability for 10 additional reptile and amphibian species occurring in different regions across the nation. The spatially-explicit forecasts also include an inventory of protected areas that fall within long-term climate refugia that are projected for each species.

Table of Contents

Amphibian Climate Change Vulnerability Assessment: Draft Report
Project team: Drs. Kyle Barrett, John C. Maerz, and Nathan P. Nibbelink
Project Coordinator: Priya Nanjappa
Warnell School of Forestry and Natural Resources
University of Georgia

Project Summary

Climate change is widely recognized as a large-scale threat to wildlife; however, generating precise predictions of ecological responses to changing climates is exceedingly difficult. This difficulty exists because of inherent uncertainties associated with climate forecasting and additional uncertainly in the relationship between species distributions and climate. Nevertheless, because ectotherm physiologies are tightly linked to ambient conditions, it is reasonable to assume that many ectotherm species will respond strongly to shifting climate patterns. This expectation is especially warranted for amphibians and reptiles, as a large body of evidence indicates their ecology depends heavily on temperature and precipitation patterns. Because of this dependency, we conducted a climate change vulnerability assessment for amphibians and reptiles throughout the United States, with an emphasis on amphibians of the southeast. The species to be included in the assessment were determined by federal listing of endangered and threatened species; multi-state rankings of Rare, Threatened, and Endangered status; and in part by inclusion on a state's Species of Greatest Conservation Need list. This assessment provides spatially-explicit and species-specific information on the amount of habitat projected to be lost due to climate change, the areas of a species' range most susceptible and most resilient to changing climates, and an assessment of currently protected habitats that may be most valuable for long-term conservation efforts.

The vulnerability assessment rests largely on the creation of species distribution models. The process of constructing data sets to support the modeling effort required a partnership

between our modeling team and state partners with access to georeferenced records for the species of interest. Given the significant number of steps involved in creating a georeferenced database for herpetofauna across the United States and interfacing with multiple state partners, our group has largely focused detailed results on amphibian species in the southeastern US (21 species); however, we have generated model results for 10 other reptile and amphibian species across the US. We primarily focused on (1) specific areas where the climate in 2050 would match the climates preferred by species today, and (2) the ranking of species vulnerabilities relative to other regional herpetofauna.

We found that, in general, species with larger ranges are projected to be less vulnerable to climate change than species with smaller ranges. Models indicate that, on average, southeastern species are likely to lose the most climatically suitable habitat by 2050. Within the southeastern US, the coastal plain is a region of very high climate change vulnerability for nearly all species examined. For each projection presented throughout the document, we have examined a range of scenarios, and we use this range to represent the uncertainty associated with our modeling exercise.

Climate change is likely to result in shifting patterns of species distributions; however, species will undoubtedly differ in their sensitivity to climatic patterns. Experimental and observational evidence can help clarify which species are likely to be most sensitive to temperature and precipitation patterns. These data will be important to collect, and incorporate into projects such as this one; however, in the near term we believe species distribution models can provide decision-relevant science to support conservation.

Introduction

Climate change, in conjunction with threats such as land use change, disease, and habitat degradation, is predicted to seriously alter global biodiversity patterns (Leadley et al. 2010). For many species, the "fingerprint" of climate change can already be detected through shifts in range and phenology. For example, Parmesan and Yohe (2003) detected an average poleward shift of 6.1 km per decade for organisms as diverse as birds, butterflies, and alpine herbs. Given the strong correlation between climate and the distribution of some ectotherms (Buckley and Jetz 2007), it is reasonable to believe that climate change may have especially strong impacts on ectothermic taxa (Aragon et al. 2010) such as reptiles and amphibians.

Evidence for the influence of climate on amphibian and reptile ecology is considerable. Buckley and Jetz (2007) document the importance of long-term temperature and precipitation patterns in predicting regional species richness patterns of amphibians. Sinervo et al. (2010), demonstrated the relationship between thermal tolerances, population demography, and extinction risk in several lizard species. In addition, researchers have demonstrated that climatic niches are often conserved over evolutionary time, such that species and clades tend to remain within their historical climate regimes (Kozak and Wiens 2010). Collectively, these results not only suggest that climate is an important determinant of evolutionary patterns for amphibians and reptiles, but that climate change may have strong current and future influences on this group. Other studies have clearly demonstrated the influence of temperature and precipitation on breeding patterns in amphibians. For the common toad (*Bufo bufo*), Reading (2007) documented a negative correlation between winter temperatures and female body condition index the following spring. The warmer winter temperatures forced female metabolism to elevate such that fat reserves were processed throughout the species' inactive period. This, in turn, left fewer fat reserves available for egg deposition during the spring breeding period. The influence of precipitation on breeding patterns has also been documented. Jensen and colleagues (2003) document a negative relationship between breeding season rainfall and the number of egg mass counts in two ponds for the gopher frog (*Lithobates capito*). For reptiles, it may be that increasing temperatures could actually enhance breeding opportunities or expand ranges in more temperate climates (Gregorio et al. 2012), with more negative consequences being realized at lower latitudes (Sinervo et al. 2010). In general, these results highlight the importance of assessing the amount of climate change that reptiles and amphibians will experience. Our model-based assessment provides a strong starting point for establishing monitoring efforts, prioritizing species in need of conservation, and locating places that will (and will not) serve as potential refugia from climate change. All of these facets of wildlife management will only increase in importance as in the face of changing climates.

The United States contains over hundreds of reptile and amphibian species, so a comprehensive climate change vulnerability assessment for the country was not logistically feasible for the current project. Instead, we used existing filters and/or prioritization schemes to select focal species, and we tried to represent a broad swath of US geography. Specifically, when selecting species we focused primarily on those that were listed under the Endangered Species Act as either Threatened or Endangered, or listed as Threatened or Endangered under by more than one state. We also made a point to select at least two species with ranges largely restricted to one of five regions of the country (Northwest, Southwest, Midwest, Northeast, and Southeast US; Table 1).

The southeastern United States represents a global hotspot of amphibian diversity, with nearly 200 species in the region – over 50 of which are regional endemics (Duellman 1999). The southern Appalachian Mountains and the Gulf Coastal Plain region are the areas containing much of the southeastern biodiversity and endemism. A recent analysis of potential climate change effects on plethodontid salamanders in the Appalachian Mountains indicated this region could face drastic shifts in species composition within the next 10 – 40 years (Milanovich et al. 2010). As a result of the significant amphibian diversity within the southeast and indications that a subset of this diversity may face drastic loss of suitable habitat under some climate change scenarios, we selected eight southeastern states within which to focus a detailed vulnerability assessment of amphibians that complements our national assessment.

Because climate change represents a global threat to biodiversity, analyses attempting to determine which species and habitats will be most affected must be large-scale. While large-scale studies of natural history and empirical data collection are important (Lindenmayer and Likens 2011), they are often prohibitively expensive, and require more time to complete than is reasonable given the immediate need for tools to help climate change-related conservation planning. As a result, model-based approaches can offer short-term solutions and insights that assist with species prioritization and, in some cases, the identification of spatially-explicit expected climate change effects. Because of these advantages, we used a species distribution modeling approach to support our climate change vulnerability assessment of southeastern amphibians.

Specifically, our goal for this project was two-fold. First, we sought to work with state partners to identify a list of species that were of foremost concern with respect to climate change. This step helped to ensure that the results of our climate change vulnerability assessment would have direct relevance to the conservation and management efforts that are being employed at the state level. Second, we generated models of climatic suitability for the priority species so that we could project climatic suitability onto a range of future climate scenarios. This process allowed us to understand (1) which species are most likely to be influenced by climate change, and (2) what areas are likely to provide significant climate risk/refugia to large numbers of species.

Methods

Species selection

The vulnerability assessment was conducted on two groups of species. First, a national species list was assembled largely, but not exclusively, from species that were listed at either the federal or state-level as threatened or endangered. This list was not exclusively developed from the listing categories because we also wanted to ensure each of five geographic regions in the US was represented by at least two species (Table 1). The second group of species was exclusively drawn from amphibians in the southeast. Candidate species for this modeling effort were determined through cooperation with eight state fish and wildlife agencies in the southeast (Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee). We contacted state herpetologists tasked with managing and/or identifying herpetofauna of conservation concern in the state, and asked them to provide us with the five amphibians they were most concerned with in the face of changing climates. We provided these contacts with a list of amphibians that had been generated from state lists of Species of Greatest Conservation Need from which to make their selection. This list was provided as a way to focus their efforts on pre-existing prioritization schemes. Because we wanted to address conservation needs at a national scale, rather than solely within a state, we asked each state to consider not including a species if it was a priority within their state boundaries, but common throughout the rest of its range; however, we did not make this request an essential criterion in their species selection process (Table 2).

Table 1. Species selected for the national reptile and amphibian climate change vulnerability assessment.

Species	Taxa	Listing status
Northwest		
Rana pretiosa	Anura	State Endangered (WA)
Actinemys marmorata	Testudines	State Endangered (WA
Southwest		
Rana muscosa	Anura	Federal Endangered
Gopherus agassizii	Testudines	Federal Endangered, State Threatened (CA, NV, UT)
Midwest		
Heterodon nasicus	Squamata	State Threatened (IL)
Plestiodon septentrionalis	Squamata	None
Northeast		
Clemmys muhlenbergii	Testudines	Federal Threatened, State Endangered (CT, DE, GA, MA, NJ, NY, PA, VA), State Threatened (MD, NC, SC)
Crotalus horridus	Squamata	State Endangered (CT, GA, IN, MA, NH, NJ, OH, VT, VA), State Threatened (IL, MN, NY, TX)
Southeast		
Gopherus polyphemus	Testudines	Federal Threatened, State Endangered (MS, SC), State Threatened (FL, GA, LA)
Drymarchon couperi	Squamata	Federal Threatened, State Endangered (MS), State Threatened (FL, GA)

Species distribution modeling

We constructed species distribution models for all of the species included in the vulnerability assessment. We used an inductive, presence-only modeling approach (Maxent), using only climatic variables, to model species' climatic distributions. The first step of collecting locality data on each species was accomplished through the publically accessible museum database portal HerpNet (www.herpnet.org). As with nearly any analysis, the quality of the final output hinges on the amount of data available for input. For our approach, we set a goal of obtaining 30 locality records (latitude/longitude coordinates) for each modeled species. Many of our selected species fell short of that goal after searching the public databases. For these species we addressed data shortages by appealing directly to state inventories for additional locality records. For several species, many locality points were clustered closely together. Such clustering likely represented areas that were sampled more frequently, and not areas of high climatic suitability for the species of interest. This kind of biased distribution data can result in biased model results (Veloz 2009). To correct for this bias, we haphazardly selected a single point among clusters of points that were within 5 km of one another, and then we removed the remaining nearby localities. After removing clusters and errant point locality data were able to meet our goal of 30 locality records for all of the species on our national list, and 13 of the 21 species in the southeast. For an additional four southeastern species, we had at least 20 records.

To assess current and projected climate envelopes for species we selected 11 biologically relevant climate measurements (BIO 1 – 3; 7 – 9; and 15 – 19) from among 19 temperature and rainfall variables (www.worldclim.org/bioclim) that were synthesized from long-term monthly averages (1950 – 2000). These variables were selected based on a previous analysis that identified them as exhibiting low pairwise correlations and having relevance to amphibian biology (Rissler and Apodaca 2007). These climate variables were then intersected with locality data for each species as well as background points. We generated background points by randomly placing 10,000 points within a 50 km buffered range of the species (range maps were acquired from the IUCN's spatial data download page: http://www.iucnredlist.org/technicaldocuments/spatial-data#amphibians). We used software (Maxent, Version 3.3.3a) that relies on principles of maximum entropy to determine the joint distribution of climatic conditions correlating with presence records of each species (Phillips et al. 2006). The approach estimates climatic suitability by comparing the values of environmental variables in places where the species is known to occur (locality records) to the same data at background point localities. After the program estimates preferred climates, it maximizes the entropy in the probability distribution of suitability across all areas of the distribution where empirical observations are lacking. These preferences were then projected onto downscaled projections of climate change for the 11 climate variables based on two different CO_2 emissions scenarios (the B2a "medium" and A2a "high" scenarios) as generated by two different general circulation models or GCMs (Met Office's Hadley Centre and the Canadian Centre for Climate Modelling and Analysis). The current climate averages and the projected climate changes were all downscaled at approximately 1 km^2 (30 arc seconds). The output from the species distribution models provides a continuous surface from 0 – 1 that represents low to high probability that the climate is suitable for the modeled species. For analyses where a "yes or no" answer to suitability is required, we evaluated three different thresholds for identifying whether or not a particular climate is suitable. These thresholds represented a range from conservative to liberal estimates of what might be deemed suitable habitat (i.e., some were more inclusive of a broader range of climate zones than others). The thresholds evaluated were "fixed cumulative value 10" (the threshold that results in a 10% omission rate of training data), "minimum training presence" (the minimum value for which all presence localities are correctly predicted), and "maximum training sensitivity + specificity." The two CO_2 futures crossed with two GCMs and three thresholds yielded a total of 12 binary models evaluated for each of the species. After the models were generated, we clipped the resulting prediction map to a 50 km buffer of the currently suspected range for each species. This is a very generous estimate of the ability of most amphibians and reptiles to track their respective climate envelopes via dispersal.

Data analysis and reporting

We report on species-specific output for all modeled species. Species-specific distribution model results are reported from the ensemble of two GCMs, each of which was examined across three thresholds. This resulted in six possible outcomes for a given CO_2 emissions scenario. Each CO_2 scenario is reported separately, because the climate outcomes under each represent distinct (non-overlapping) future outcomes. In addition to the spatially-explicit depiction of shifts in climatic suitability, we generated tables for each species that rank protected areas within states based on the amount of climatically suitable habitat the protected area is projected to have by 2050 for a given species. Protected areas were obtained from the Protected Areas Database of the United States (PAD-US), hosted by the USGS Gap Analysis Program (www.protectedlands.net/padus/). These areas do not necessarily confer protection on the species featured in this report, but rather are areas of public land ownership, management, and conservation lands. The database also includes voluntarily provided privately protected areas. Rankings were done in a weighted manner, such that areas projected to remain climatically suitable by more than one model were weighted heavier than those areas only appearing as suitable in one model projection. For the group of amphibians that were part of the southeastern analysis, we limit our listing of protected areas only to the eight focal states. For some species on the national list (Table 1) we did not list all protected areas with climatically suitable in 2050 because the number of areas was well over 1,000. Finally, we ranked climatic sensitivity across species by examining the average amount of climatic suitability projected to be lost across all model scenarios.

To identify areas within the southeast that are likely to lose climatic suitability for a large number of species of concern, we combined individual species models and examined areas of change between current and projected models. We began by estimating the number of priority species with overlapping ranges (per 1 km^2 grid cell), defined here as the number of overlapping species models from a given threshold (as listed above). We then estimated the number of overlapping ranges per cell for 2050 across all 12 scenarios (2 GCMs x 2 CO_2 futures X 3 thresholds), and calculated the difference between future and current values. This calculation resulted in 12 estimates of change in species number between now and 2050 for each 1 km^2 grid cell in the focal southeastern states. These 12 estimates were averaged to allow for a depiction of mean loss across all models. We also calculated the standard deviation across the 12 estimates to facilitate a spatial evaluation of the areas with the greatest uncertainty in species loss. In sum, these analyses allow for a large scale assessment of which areas are projected to be most sensitive (and most resistant) to climate change with respect to the priority species identified in our study.

Interpreting results

Throughout this document phrases like "climatic suitability" or "habitat suitability" are referring to the modeled preference of specific climate regimes for focal amphibians. It is unlikely that any organism has its distribution set solely by climatic factors, so it is important to recognize that a decrease in climatic suitability (or a complete loss) does not necessarily signal species extirpation from that area. Modeled losses of climatic suitability should be interpreted as a signal that long-term temperature and precipitation patterns currently selected by the species will no longer be present in a given area in the future. As described in the introduction, there is ample evidence for amphibians to indicate that such losses may translate to demographic concerns for species; however, it will take more detailed analyses to adequately characterize specific concerns. This analysis should be seen as a first step toward recognizing species that are most at risk of exposure to changing climate, and as a way to identify key areas of climate sensitivity for multiple species of concern.

Species-specific models, which serve as an end product in this report as well as a tool for building maps of the number of overlapping priority species ranges and the expected change in the this overlap, can be evaluated based on several metrics of model fit. In the section "Interpreting Species Specific Results" we detail how the test statistics should be interpreted. In addition, we provide some general guidelines for evaluating how useful (i.e., reliable) a given model may be.

Results

Species selection of southeastern species by expert opinion

Twenty-one species (12 genera) were identified across the eight states we surveyed (Table 1). Fifteen of the species were salamanders, and the remaining six were frogs. Ten of the species were identified as one of the top-five species of concern (with respect to climate change) by more than one state in the southeast. The Green Salamander (*Aneides aeneus*) was the most frequently identified species of concern (listed by 5 states). While some species were difficult to characterize with respect to ecoregion (n = 5), the remaining species can be roughly attributed to either the Appalachian Mountains (n = 6), the Piedmont (n = 2), or the Coastal Plain (n = 8).

Table 2. Species selected through state fish and wildlife agency cooperation for a southeastern US climate change vulnerability assessment. Values in parentheses indicate the species was identified as a priority by more than one state.

Salamanders	Frogs
Ambystoma cingulatum (2)	*Hyla andersonii* (2)
Ambystoma tigrinum	*Pseudacris brachyphona*
Amphiuma pholeter	*Pseudacris ornata*
Aneides aeneus (5)	*Lithobates capito* (3)
Cryptobranchus alleganiensis (3)	*Lithobates okaloosae*
Desmognathus aeneus (3)	*Lithobates sylvaticus*
Desmognathus welteri	
Desmognathus wrighti	
Hemidactylium scutatum (2)	
Necturus alabamensis	
Notophthalmus perstriatus (2)	
Plethodon ventralis	
Plethodon websteri (2)	
Plethodon wehrlei (2)	
Plethodon welleri	

Species-specific results

All but three species (*H. scuatum*, *R. muscosa*, and *H. nasicus*) are, on average, predicted to lose climatically suitable habitat across all scenarios examined (Table 3, Table 4). The southeastern list of species losing the vast majority of climatically suitable habitat by 2050 (≥ 95 %) is dominated by species from the Coastal Plain (five out of the eight present in the study), and also includes two species from the Appalachian Mountains, and one species from the Piedmont (Table 3). On the national list showing percent climatically suitable habitat lost (Table 4), two coastal plain reptiles top the list (both losing ≥ 95%). Many of the western species are projected to lose relatively little climatically suitable habitat; however, *G. agassizii* was an exception (mean loss = 86%). Models of *C. muhlenbergii* and *C. horridus* should be interpreted with caution. These species have ranges that span relatively wide areas; however, as noted on the pages of this report specifically addressing those species, we were unable to get range data in some of the areas where the species is known to be quite common.

For all species except *A. cingulatum*, *L. okaloosae*, and *N. alabamensis* we identified at least two protected areas that would contain climatically suitable habitat by 2050 under some scenario. For the southeastern focal species the median number of protected areas projected to remain climatically viable was 40 (range = 2 – 660). Two protected areas were identified for *N. perstriatus* and *P. websteri* despite the fact that they are reported to have no climatically suitable habitat remaining by 2050 in Table 3. This discrepancy results because values in Table 3 were rounded up, and the remaining climatically suitable habitat for these species is exceeding low by 2050. The sum of protected areas for each southeastern amphibian species with at least some protected habitat had a median value of 640,202 ha, with the smallest sum associated with projections for *P. websteri* (3,281 ha) and the largest with *A. tigrinum* (13,189,000 ha). It is difficult to make comparisons of patterns in projected protected areas between the southeastern amphibian species analyses (Table 2) and the analyses of species from the national list (Table 1). This is because (1) the examination of protected areas for the southeastern focal list was limited to eight southeastern states (regardless of species range) and (2) a disproportionate number of protected areas in the United States are in the western half of the country. For all species we have created a section of this report that contains maps depicting the location of climatically suitable habitat in 2050. For all species where practical, we also generated a table listing the protected areas containing such habitat. Such a table was not possible for *A. marmoratus*, *H. nasicus*, and *C. horridus* because of their very large range size and the corresponding very large number of protected areas that are expected to remain climatically viable for these species.

Species richness patterns in the southeastern US

The decrease/increase in overlapping priority species ranges between current and future climate suitability projections ranged between mean values of +2 and -7 species (Fig. 1). The vast majority of land within the southeast is projected to either maintain current climatic suitability for the same number of species as currently seen, or to lose climatic suitability for at least one or more species. The only regions in the southeast projected to show an increase in species richness by 2050 were a few scatter cells in the Appalachian mountains located in Swain and Haywood Counties, NC and in Sevier County, TN. Because these regions are collectively so small (totaling 210 km^2), and likely represent mountain top refugia, it would be difficult to imagine these sites representing critical future habitat. Three regions, the Florida Panhandle, the Appalachian Plateaus of north-central Alabama and northwestern Georgia, and the Ridge and Valley Appalachian regions of Tennessee contained the areas with at least a mean of 4 species lost between current estimates and 2050 projections. Two of these regions (the Florida Panhandle and the Appalachian Plateaus of north-central Alabama) were also regions with greater variance around the mean of the 12 scenarios (Fig. 2). In particular, the high mean diversity loss within northern Alabama and the panhandle of Florida was subject to considerable variation among predictions.

Discussion and conclusions

The reptile and amphibian species we modeled were largely comprised of species already of significant national, regional, or state concern (Table 1). Several of these species have ranges that extend over large north-south gradients, and such species appeared to have somewhat stable climatic niches relative to species with smaller ranges. Nevertheless, it is possible that some of these species exhibit local physiological adaptations, which would render climate-based models assembled from range-wide data less informative. It is noteworthy that the areas across the United States where we saw the greatest percentage of projected loss in climatically suitable habitat are not the same areas projected to be hotspots of change (Diffenbaugh et al. 2008). Specifically, while Diffenbaugh et al. (2008) suggest that the southeastern coastal plain is an area that will see relatively small changes in measures of temperature and precipitation, we saw some of the most dramatic species responses in this region. While it is not clear why this should be the case, it is possible that the specific variables correlating with individual species' distributions are swamped out by the broad range of variables appearing in the hotspots of change analysis.

Southeastern amphibians identified as being of primary conservation concern in the face of climate change included taxa encompassing a range of natural history strategies and habitat types. Species primarily restricted to the Coastal plain made up over ⅓ of the total list, with species from the Appalachian Mountains being the next most common. These two regions are centers of endemicity in the US, so it is not unexpected that these zones would contain many species of conservation concern. Twice as many salamanders as frogs made the list; however this was not unexpected given the initial list of Species of Greatest Conservation Need (SGCN) presented to the state herpetologists. On that list, approximately ⅕ of the species were frogs, so representation increased (to over ¼ of the total species) on our list of 21 species. The Green Salamander, *Aneides aneus* appeared on more "top five" lists than any other species; however, because it also appears on the SGCN list for seven of our eight focal states, this result was not particularly surprising.

We suggest the species-specific results offer two primary tools. First, the maps identifying areas projected to be climatically suitable for a given species in 2050 provide a means for identifying zones of climatic vulnerability and/or refugia for species relative to their current strongholds. Areas that appear to be vulnerable (i.e., areas where the species currently exists, but that do not show future climatic suitability) are not necessarily destined for species extirpation; however, in these areas not even one model projected temperature and precipitation patterns will match what the species currently experiences. As a result, it is reasonable to assume these areas will present some physiological stresses to species that are already of conservation concern. As described in the Methods, these maps are ensemble projections of 6 different model scenarios (2 GCMs x 3 thresholds), and as a result they provide an opportunity for land managers to explicitly incorporate model uncertainty into any on-the-ground decisions involving these maps. A second species-specific tool that we generated to assist managers are tables that summarize protected areas containing at least some long-term climatically suitable habitat. Focusing on protected areas within the climatically suitable zones offers a way to prioritize management efforts. We ranked protected areas within each state based on weighted score of how much habitat within the protected area was projected to remain climatically suitable (and how suitable on a scale of 0 – 1 that habitat was projected to be). State and federal wildlife experts will be best positioned to recognize which protected areas that we have presented may also contain on-the-ground habitat features that are necessary for a given species. We suggest maximizing this dynamic between such local habitat features and suitable climate to ensure long-term species occupancy.

Taken together, the maps and the tables of protected areas with long-term climatic viability also offer opportunities for prioritizing conservation efforts on private or other lands that occur outside of protected areas. Specifically, state fish and wildlife agencies, private landowners, and/or land trusts could examine areas modeled to have long-term climatic viability for species of interest, but that lie outside of protected habitats. Such areas may warrant significant consideration during future habitat protection/acquisition efforts – especially if the areas enhance connectivity between lands currently afforded some measure of protection.

Regions where loss of climatic suitability is expected for a large number of priority southeastern amphibian species (e.g., ≥ 4) represent areas where conservation efforts stand to have the largest impact by enhancing the adaptive capacity of habitats and/or species. Currently, it is beyond the mandate of state fish and wildlife programs to manage species that do not occur currently within their state at this time. Additionally, many states allocate management dollars to species that have a limited distribution within the state, but may be quite common in other portions of their US or global range. In the context of shifting climates and shifting species ranges, we advocate for a broad, coordinated view of species management. To the extent that state fish and wildlife agencies can examine and coordinate management priorities across political boundaries, this cooperation will most likely (1) enhance success for species monitored/managed by more than one state, and (2) prevent wasted resources on species that may have low probabilities of remaining within the boundaries of a state, but that are not likely to be in danger of regional or global extirpation.

Projected shifts in temperature and precipitation are accompanied by a large amount of uncertainty (Christensen et al. 2007), and this uncertainty is compounded by the lack of knowledge surrounding how amphibians and reptiles will respond to a given shift in climate. While this uncertainty cannot be ignored, modeling efforts do provide a means to initiate immediate planning for long-term scenarios. We evaluated medium (B2a) and high (A2a) CO_2 scenarios and two different GCMs that attempt to capture climate response to those scenarios. In addition, we examined three amphibian response thresholds, which mimic the tolerance of each species to variation in future climates relative to currently occupied habitat. By doing this, our analysis has embraced uncertainty and incorporated it directly into our results. Additionally, we have modeled at a spatial scale that likely reduces the chance of over-estimating climatically suitable habitat (Seo et al. 2009). Many states are currently revising State Wildlife Action Plans and climate change will be explicitly incorporated into many of those revisions (A. Choudhury, pers. comm.). It is essential that the best available science is brought to bear on such revisions, and it is a matter of fact that when dealing with climate change projections even the best science contains many unknowns. The products we present here provide an immediate means for addressing long-term planning in a changing world, and they do so by acknowledging a range of possible outcomes.

Future analyses can help to not only reduce the uncertainty associated with modeling, but to move beyond modeling to address approaches that enhance the adaptive capacity of species. In many cases, it appears that our best tools for dealing with climate change are tools that many wildlife managers and conservationists use on a daily basis (Mawdsley et al. 2009), including maintaining or improving habitat quality and/or connectivity. It remains to be seen what management efforts, specifically, will mitigate the effects of changing climate on amphibians and reptiles. Future solutions may be as drastic as engineering breeding habitat for species (Shoo et al. 2011) and moving species to new locations (i.e., managed relocation), or as simple as providing the high quality wetlands and uplands already known to be essential for the persistence of many species.

Table 3. Proportion of habitat that is projected to be climatically unsuitable by 2050 for each of the southeastern modeled species. N represents the number of localities used to build the model, and Test AUC is a measure of model quality (see "Individual Species Results" for more detail). Black cells indicate 100% of climatically suitable habitat is projected to be lost. Species are ranked in order of the mean loss across model types. All modeled scenarios and thresholds are depicted below. Threshold abbreviations: MTP = minimum training presence, F10 = fixed cumulative value 10, MTP = maximum training sensitivity plus specificity. See methods for threshold definitions. Negative values indicate the species is projected to gain habitat under a given scenario.

			Hadley						Canadian						
			A2a			B2a			A2a			B2a			
Species	N	Test AUC	MTP	F10	MTR	MTP	F10	MTR	MTP	F10	MTR	MTP	F10	MTR	Mean loss
A. cingulatum	24	0.69													1.00
L. okaloosae	48	0.93													1.00
N. alabamensis	17	0.84													1.00
N. perstriatus	41	0.76													1.00
P. websteri	24	0.83				0.98	0.98								1.00
P. ventralis	32	0.70	0.97	0.98	0.98	0.97	0.98	0.98	0.97	0.98					0.98
L. capito	152	0.85	0.92			0.94	0.99		0.92			0.90	0.98		0.97
D. welteri	25	0.83	0.91	0.91	0.90	0.90	0.90	0.87				0.97	0.98		0.95
D. aeneus	22	0.98	0.98	0.97	0.91	0.98	0.97	0.94	0.95	0.92	0.80	0.97	0.96	0.88	0.94
A. aeneus	62	0.72	0.92	0.93	0.92	0.92	0.93	0.94	0.89	0.92	0.90	0.95	0.95	0.95	0.93
P. wehrlei	93	0.73	0.91	0.93	0.95	0.89	0.94	0.98	0.95	0.98		0.80	0.90	0.95	0.93
H. andersonii	52	0.82	0.86	0.84	0.82	0.90	0.95	0.95	0.90	0.94	0.97	0.90	0.92	0.93	0.91
D. wrighti	30	0.98	0.92	0.94	0.94	0.87	0.93	0.91	0.89	0.91	0.90	0.89	0.88	0.87	0.90
P. welleri	14	0.94	0.78	0.77	0.82	0.78	0.82	0.80	0.97	0.97	0.98	0.90	0.87	0.92	0.87
P. brachyphona	53	0.80	0.85	0.85	0.93	0.80	0.80	0.83	0.88	0.88	0.96	0.84	0.83	0.88	0.86
*A. pholeter**	14	0.37							0.82	0.80	-1.56	0.99	0.99	0.89	0.75
C. alleganiensis	83	0.91	0.84	0.96	0.99	0.78	0.97	0.98	0.47	0.52	0.51	0.40	0.59	0.66	0.72
*P. ornata**	12	0.62	0.85	0.88	0.60	0.90	0.92	0.74	0.72	0.77	0.11	0.69	0.74	0.28	0.68
A. tigrinum	32	0.82	0.30	0.31	0.29	0.37	0.44	0.59	0.23	0.16	0.86	0.30	0.24	0.87	0.41
L. sylvaticus	451	0.94	-0.04	0.42	0.57	-0.03	0.35	0.46	-0.15	0.11	0.25	-0.09	0.02	0.17	0.17
H. scutatum	197	0.84	0.33	-0.22	0.96	0.25	-1.62	0.92	-6.47	-5.88	0.40	-7.32	-7.50	0.18	-2.16

*Low test AUC values indicate poor model quality for these species. Results are likely unreliable.

Table 4. Proportion of habitat that is projected to be climatically unsuitable by 2050 for each of the species selected as part of the national assessment. N represents the number of localities used to build the model, and Test AUC is a measure of model quality (see "Individual Species Results" for more detail). Black cells indicate 100% of climatically suitable habitat is projected to be lost. Species are ranked in order of the mean loss across model types. All modeled scenarios and thresholds are depicted below. Threshold abbreviations: MTP = minimum training presence, F10 = fixed cumulative value 10, MTP = maximum training sensitivity plus specificity. See methods for threshold definitions. Negative values indicate the species is projected to gain habitat under a given scenario.

			Hadley						Canadian						
			A2a			B2a			A2a			B2a			
Species	N	Test AUC	MTP	F10	MTR	MTP	F10	MTR	MTP	F10	MTR	MTP	F10	MTR	Mean loss
D. couperi	422	0.78	0.89	0.93	0.93	0.97			0.98			0.99			0.97
G. polyphemus	448	0.76	0.92	0.99		0.96	0.97	0.99	0.87	0.90	0.94	0.93	0.96	0.97	0.95
G. agassizii	107	0.87	0.84	0.95	0.97	0.89	0.97	0.99	0.52	0.94	0.98	0.42	0.93	0.98	0.86
C. horridus	180	0.73	0.87	0.80	0.97	0.76	0.86	0.90	0.56	0.57	0.52	0.49	0.55	0.50	0.70
P. septentrionalis	78	0.80	0.63	0.67	0.83	0.54	0.71	0.92	0.46	0.89		0.30	0.37	0.79	0.68
C. muhlenbergii	105	0.87	0.21	0.48	0.74	0.31	0.54	0.75	0.32	0.35	0.41	0.36	0.44	0.37	0.44
R. pretiosa	38	0.70	0.37	0.36	0.33	0.28	0.27	0.08	0.37	0.36	0.32	0.27	0.28	0.30	0.30
A. marmorata	344	0.82	0.17	0.18	0.07	0.19	0.22	0.16	0.04	0.20	0.17	0.00	0.12	0.11	0.13
R. muscosa	73	0.84	-0.12	-0.25	-0.47	-0.09	-0.15	-0.18	-0.22	-0.33	-0.54	-0.16	-0.26	-0.48	-0.27
H. nasicus	374	0.86	-0.94	-0.15	0.01	-0.84	-0.17	-0.02	-1.13	0.10	0.29	-1.11	0.06	0.24	-0.30

Figure 1. Mean change in the number of overlapping priority amphibians species in the southeastern US (based on climatic suitability) as calculated from 12 different change scenarios between current estimates and 2050 projections. See Methods for detail on the generation of future projections.

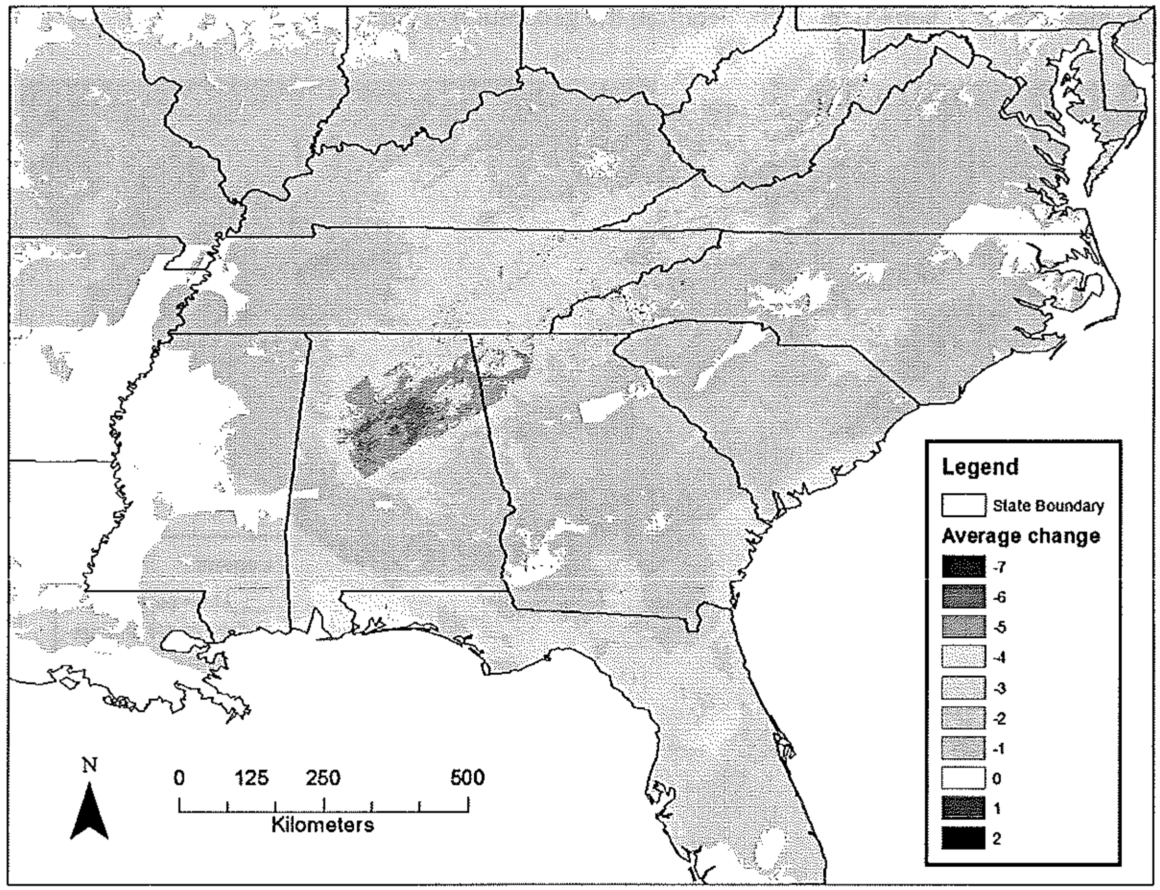

Figure 2. The spatial distribution of standard deviation values resulting from 12 different change scenarios in priority southeastern amphibian species overlap (based on climatic suitability) between current estimates and 2050 projections. Caution must be used when interpreting this map, as low standard error values might result from agreement across all models or from low estimates of total species overlap. As a result, this figure is best interpreted with reference to Fig. 1. See Methods for detail on the generation of future projections.