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Use of the NatureServe Climate Change Vulnerability Index as an Assessment Tool for Reptiles and Amphibians: Lessons Learned

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Abstract Climate change threatens biodiversity globally, yet it can be challenging to predict which species may be most vulnerable. Given the scope of the problem, it is imperative to rapidly assess vulnerability and identify actions to decrease risk. Although a variety of tools have been developed to assess climate change vulnerability, few have been evaluated with regard to their suitability for certain taxonomic groups. Due to their ectothermic physiology, low vagility, and strong association with temporary wetlands, reptiles and amphibians may be particularly vulnerable relative to other groups. Here, we evaluate use of the NatureServe Climate Change Vulnerability Index (CCVI) to assess a large suite of herpetofauna from the Sand Hills Ecoregion of the southeastern United States. Although data were frequently lacking for certain variables (e.g., phenological response to climate change, genetic variation), sufficient data were available to evaluate all 117 species. Sensitivity analyses indicated that results were highly dependent on size of assessment area and climate scenario selection. In addition, several ecological traits common in, but relatively unique to, herpetofauna are likely to contribute to their vulnerability and need special consideration during the scoring process. Despite some limitations, the NatureServe CCVI was a useful tool for screening large numbers of reptile and amphibian species. We provide general recommendations as to how the CCVI tool's application to herpetofauna can be improved through more specific guidance to the user regarding how to incorporate unique physiological and behavioral traits into scoring existing sensitivity factors and through modification to the assessment tool itself.

Keywords Climate change · Vulnerability assessments · Reptiles · Amphibians · Sand Hills ecoregion

Introduction

Globally, climate change is thought to be responsible for shifts in distribution and changes in abundance for many species (e.g., Parmesan and Yohe 2003; Perry et al. 2005) and may already be responsible for at least one species' extinction (Pounds et al. 1999). Ecological modeling efforts predict high levels of species extinction rates (e.g., 15–37 %) by the year 2050, based on mid-range climate-warming scenarios (Thomas et al. 2004). If these predictions are accurate, it becomes imperative that we determine the species that are at greatest risk of climate-mediated population decline and identify any possible mechanisms to decrease that risk (e.g., Mitchell et al. 2010; Shoo et al. 2011).

Numerous studies have attempted to model the vulnerability of a species or suite of species to climate change (e.g., Midgley et al. 2002; Chin et al. 2010). A species'

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vulnerability is influenced by both its potential exposure to future climate change (to what extent temperature and precipitation patterns are expected to change within the species' range or area of interest) and how sensitive the species is to those changes. Thus, vulnerability can vary both by species and by geographic area, making it difficult for land managers to use information garnered from previous studies when making management decisions. For example, while precipitation amounts are not projected to change drastically in eastern coastal areas of the United States (US), the Midwest region is projected to experience substantially reduced precipitation (Maurer et al. 2007; Nature Conservancy 2009). Likewise, sympatric species may vary in their ability to respond to changing temperature or precipitation regimes within the same local area. For example, rat snakes (*Pantherophis alleghaniensis*, formerly *Elaphe obsoleta*) are able to facultatively shift their diel activity from diurnal to nocturnal when temperatures are high, whereas black racers (*Coluber constrictor*) from the same study site remain strictly diurnal (DeGregorio et al. 2014). Because of such variation in regional and species-specific responses, it becomes necessary to assess vulnerability for individual species within a defined assessment area.

Assessing vulnerability can require extensive knowledge about a species' life history, population demographics, and projected climatic changes within the assessment area—which collectively make vulnerability assessments a daunting task for many land managers. Numerous tools and approaches have been developed to assess species' climate change vulnerability, including bioclimatic envelope models (e.g., Maxent; Phillips et al. 2006), mechanistic niche models (Kearney and Porter 2009), and vulnerability indices (see below). The approaches vary in their assumptions, species-specific data needs, computational requirements, limitations, and how they deal with model uncertainties. Thus, the most suitable approach will be context-specific and will vary based on the types and amount of information available, temporal and geographic scales of interest, number of species to be assessed, goals of the end user, and the resources available for conducting assessments (Glick et al. 2011; Rowland et al. 2011). Vulnerability indices are one of the most commonly used approaches because they generally only require information readily available in the literature or through web-based climate tools, thereby facilitating assessment of a large number of species (Rowland et al. 2011). To simplify this task, several organizations or researchers have developed indices to assist land managers in assessing vulnerability for species of interest [e.g., US Environmental Protection Agency framework (USEPA 2009); US Forest Service's (Bagne et al. 2011); NatureServe (Young et al. 2011a); and Reece and Noss (2014)]. Although the ability to apply these indices to a broad array of taxonomic groups is generally considered to be one of their strengths (Glick et al. 2011; Young et al. 2015), few tools have been evaluated with respect to their suitability to specific taxonomic groups other than birds (e.g., Liebezeit et al. 2012; Siegel et al. 2014). Here we document our use of one of these tools, the NatureServe Climate Change Vulnerability Index (CCVI), to assess vulnerability of a suite of reptiles and amphibians, collectively herpetofauna, in the southeastern US.

CCVI is the tool most widely used by state agencies to evaluate potential effects of climate change on wildlife and incorporate climate change adaptation into state wildlife action plans (AFWA 2012; Young et al. 2015 and references therein). Although over half of these assessments have included some reptile and amphibians species (Young et al. 2015), none has explicitly evaluated the suitability of the CCVI for herpetofauna. Herpetofauna face unique challenges when confronting a changing climate (Whitfield et al. 2007; Huey et al. 2009; Sinervo et al. 2010). As ectotherms, reptiles and amphibians obtain heat from external sources and are thus strongly influenced by temperature and moisture conditions in their local environment (Willmer et al. 2000). Although collectively reptiles and amphibians can tolerate a broad range of environmental conditions, individual species vary in their thermal and moisture requirements as well as in their ability to adapt behaviorally or physiologically to rapidly changing conditions (Willmer et al. 2000). In addition, they often have limited dispersal ability relative to other vertebrates such as mammals and birds (Hillman et al. 2014), constraining their ability to shift location in response to climate change (Carvalho et al. 2010; Sahlean et al. 2014). Finally, many reptiles and amphibians are either semi-aquatic or have a bi-phasic life cycle, requiring access to both aquatic and terrestrial habitats. Based on this suite of traits, herpetofauna are likely to be particularly sensitive to large-scale climate change and may also require special consideration as to how to incorporate their unique physiological and behavioral traits into the assessment process.

We tested the use of the NatureServe CCVI as an assessment tool for herpetofauna, using the Sand Hills ecoregion of the southeastern United States as a case study. The Sand Hills Ecoregion is an area of high biodiversity, including herpetofauna (Graham et al. 2010). Collectively, reptiles and amphibians occurring within the region possess a number of ecological traits and physiological tolerances that potentially predispose them to be influenced by climate change. In addition, many exhibit strong affinities to isolated ephemeral wetlands whose hydroperiods are also likely to be altered by projected climate change (Walls et al. 2013a, b). Our specific objectives were to: (1) evaluate the use of the NatureServe CCVI as an assessment tool for reptiles and amphibians; (2) examine the influence of climate change scenario selection on assessment results; (3) assess the influence of past exposure to historical thermal and hydrological variability on perceived species sensitivity; and (4) identify any ecological characteristics specific to reptiles and amphibians that may need special consideration when applying the NatureServe assessment tool. More detailed information regarding relative vulnerability of each species, factors contributing to their vulnerability, and recommendations for prioritizing them for additional monitoring or management, will be presented elsewhere.

Methods

We used the NatureServe CCVI tool (version 2.1), which incorporates key factors thought to influence species susceptibility to climate change, including indirect exposure to climate change, species-specific sensitivity factors, and documented response to climate change (Young et al. 2011a). Some of the key characteristics of CCVI are that it: (1) is programmed in a Microsoft Excel workbook; (2) uses climate projections available as GIS layers through Climate Wizard (www.climatewizard.org); (3) requires knowledge about the distribution and life history of the focal species; (4) predicts whether a species will decline, remain stable, or increase in numbers by the year 2050 within the assessment area; and (5) identifies key factors associated with the vulnerability of the focal species (Young et al. 2011a). The workbook template and associated guidelines are available through the NatureServe website (www.natureserve.org).

We identified the suite of candidate species by comparing the boundaries of the Sand Hills Ecoregion (an area of approximately 20,790 km^2, Fig. 1; EPA Level IV classification system, http://www.epa.gov/wed/pages/ecoregions.htm) with range maps for reptiles and amphibians as depicted in Conant and Collins (1998). We were able to download distribution shapefiles from NatureServe (www.natureserve.org) for 97 (82.9 %) of the candidate species. For 16 turtles, two snakes, one crocodilian, and one salamander for which shapefiles were not available, we created maps in ArcMap 9.3 (ESRI 2009) based on Conant and Collins (1998), the same source referenced for the NatureServe maps. All range maps represented extent of occurrence, as recommended by Young et al. (2011a), due to the coarse spatial resolution of climate projection maps. We calculated species' historical and future potential exposure to climatic variation by overlaying distribution maps with climate projection data layers available at Climate Wizard (www.climatewizard.org). We evaluated potential natural and anthropogenic barriers to species dispersal by comparing distribution maps to data layers available from the Urban-Wildlife Interface (Silvis Lab, University of Wisconsin-Madison and the US Forest Service North Central Research Station, http://silvis.forest.wisc.edu/library/wuilibrary.asp).

Fig. 1 Location of Sand Hills ecoregion (*shaded area*) assessment area within the southeastern United States. Boundaries are based on Environmental Protection Agency Level IV classification system

We synthesized the life history and ecological traits for each species, relying primarily on peer-reviewed journal articles and published species accounts for each taxonomic group (Ernst et al. 1994; Wright and Wright 1994; Petranka 1998; Ernst and Ernst 2003; Gibbons and Dorcas 2004; Lannoo 2005; amphibiaweb.org). For widely distributed species, we limited our synthesis to studies conducted within the Ecoregion or the southeastern US when possible. When species-specific life history data were lacking for some traits, we typically scored those factors as "unknown" rather than relying on data for closely related species. For each species, we scored each factor based on whether future climate scenarios are likely to (in order of decreasing risk) increase vulnerability, somewhat increase vulnerability, be neutral, somewhat decrease vulnerability, or decrease vulnerability. We entered scores into the CCVI spreadsheet (Microsoft Office 2007), which generates one of the following ranks: (1) extremely vulnerable; (2) highly vulnerable; (3) moderately vulnerable; (4) not vulnerable/presumed stable; or (5) not vulnerable/increase likely. At least 10 of the 16 sensitivity factors must be scored for the CCVI to calculate a vulnerability rank.

Because the CCVI is designed to work in parallel with NatureServe's Conservation Status Assessment (CSA; Faber-Langendoen et al. 2012), it does not consider factors other than climate change that may contribute to their vulnerability or extinction risk (Young et al. 2012), and therefore, assesses their vulnerability based on climate change as an additional threat. Therefore, we compiled the global (G-ranks) and state ranks (S-ranks) for each species. When a species occurred in more than one state in our assessment area, we assigned it the S-rank reflecting greatest conservation threat. To examine the relationship between CCVI rank and CSA rank, we converted CCVI ranks to numeric values as follows: extremely vulnerable = 1, highly vulnerable = 2, moderately vulnerable = 3, presumed stable = 4, and increase likely = 5 (adapted from Reece and Noss 2014). We then tested for correlations between CCVI ranks and S-ranks using both raw species CCVI ranks and mean CCVI ranks averaged across species assigned to each G- or S-rank.

For our initial assessments, we followed the NatureServe guidance documents (Young et al. 2011a) and used the 'medium' (A1B) Emission Scenario and the Ensemble Average General Circulation Model climate projections (following the IPCC Fourth Assessment) from Climate Wizard website (www.climatewizard.org). In all cases, we used mean annual changes in temperature and the Hamon AET:PET moisture metric (a measure of moisture availability) when estimating exposure to future local climate change.

Additionally, we selected a subset of 19 species from each taxonomic group (three anurans, five salamanders, four turtles, five snakes, and two lizards) to conduct subsequent sensitivity analyses. We intentionally selected species that spanned the range of CCVI ranks initially assigned (i.e., from presumably stable to extremely vulnerable) and that varied in their ecological attributes (e.g., we included both terrestrial and aquatic species). To examine the effects of climate uncertainty on perceived vulnerability, we individually varied ensemble climate projections (ensemble lowest to ensemble highest) and emissions scenarios (lowest to highest), and compared CCVI ranks across the resulting climate/emission combinations. Next, we assessed the effects of assessment area size on CCVI rank. Two sensitivity factors—historic thermal niche and historical hydrologic niche—consider the degree to which a species has experienced temperature and moisture variation within the assessment area over the past 50 years. We recalculated CCVI ranks by scoring factors related to historical exposure to climate variability based on species' entire geographic distribution.

Finally, we identified additional physiological, ecological, and behavioral characteristics common in reptiles and amphibians that likely influence species' vulnerability to climate change but that were not explicitly considered in the NatureServe scoring guidance. For each characteristic, we evaluated whether it was likely to increase or decrease a species' vulnerability to climate change and determined the proportion of species in each taxonomic group that exhibited the characteristic. Finally, we suggest which CCVI sensitivity factors are most relevant to, and thus most easily adapted to incorporate, the characteristic of interest. For each of these characteristics, we relied as much as possible on published species accounts specific to the southeastern US (Gibbons and Dorcas 2005; Lannoo 2005; Buhlmann et al. 2008; Dorcas and Gibbons 2008; Jensen et al. 2008; Gibbons et al. 2009; Mitchell and Gibbons 2010).

Results

A total of 117 reptile and amphibian species had geographic distributions that overlapped with the Sand Hills ecoregion: 29 anurans, 22 salamanders, 16 turtles, 38 snakes, 11 lizards, and one crocodilian. We were able to score the minimum number of sensitivity factors (10) required to calculate a rank for all species we evaluated. Number of factors scored ranged from 11 to 16 (median = 13). The most common factors for which species-specific data were not available were phenological response to climate change (73.5 % species), genetic variation or genetic bottleneck (70.1 %), and dispersal and movement (17.1 %). We did not score any of the optional factors related to documented or modeled response to climate change because information was available for only a small proportion of species. Monte Carlo simulations performed by CCVI resulted in confidence ranking of very high for all species except four-toed salamander (*Hemidactylium scutatum*), which was considered to have only moderate confidence.

Most species, particularly amphibians and snakes, were predicted to have some degree of vulnerability to climate change, with 46.2 % being moderately vulnerable, 29.0 % highly vulnerable, and 10.3 % extremely vulnerable (Fig. 2). Only 14.5 % were presumed stable and none were considered likely to increase. Predicted vulnerability to climate change tended to increase with conservation threat status, as measured by G-ranks and S-ranks. Mean CCVI ranks were moderately correlated with S-rank ($r^2 = 0.727$) and strongly correlated with G-rank ($r^2 = 0.997$; Fig. 3), but no significant pattern was detected between raw CCVI ranks and either S-rank ($r^2 = 0.437$), or G-rank ($r^2 = 0.397$).

All species we evaluated were predicted to experience a 2.2–2.4 °C increase in temperature, the same projected for the entire ecoregion. In contrast, only 18.1 % of the continental US is anticipated to experience such moderate changes (severity categories 1–2), with 81.9 % predicted to experience more severe temperature increases (categories 3–5; Fig. 4). Sandhills species were also expected to experience only moderate decreases (severity category 3; Fig. 5)

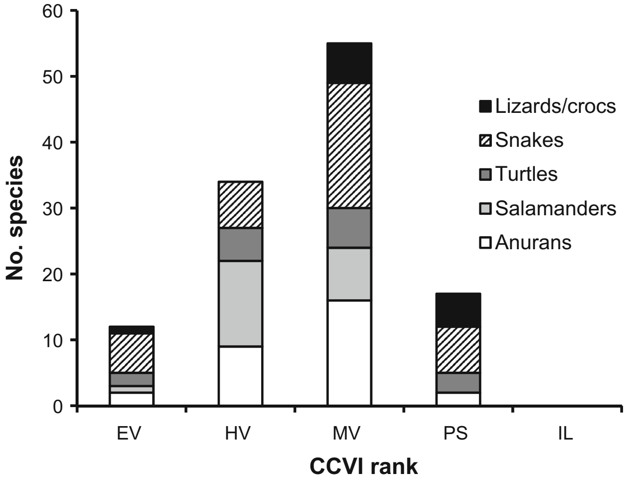

Fig. 2 Number of reptile and amphibians species (by taxa) ranked as extremely vulnerable (*EV*), highly vulnerable (*HV*), moderately vulnerable (*MV*), presumed stable (*PS*) or increase likely (*IL*) to climate change in the Sand Hills portion of their range. Vulnerability ranks were assigned using NatureServe's Climate Change Vulnerability Index

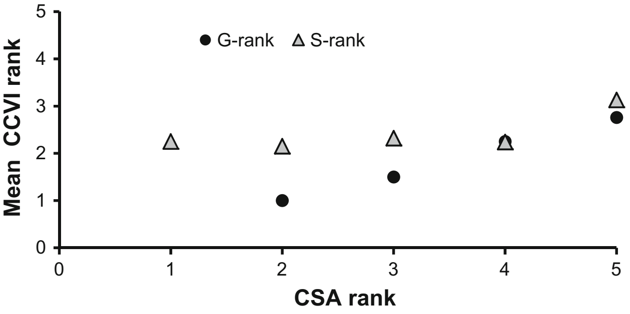

Fig. 3 Relationship between NatureServe's conservation status assessment ranks [using both global ranks (G-ranks) and state ranks (S-ranks)] and mean Climate Change Vulnerability Index (CCVI) rank for the 117 reptile and amphibian species evaluated for the Sand Hills ecoregion of the southeastern US. CCVI ranks were converted to numeric values as follows: extremely vulnerable = 1, highly vulnerable = 2, moderately vulnerable = 3, presumed stable = 4, and increase likely = 5

in moisture, with 80.45 ± 0.76 % of species' ranges within the assessment area assigned to severity category 3 and the remainder experiencing even less severe decrease. In contrast, 51.9 % of the continental US is expected to experience more severe decreases in moisture (categories 4–6; Fig. 5). Although projected average annual change in moisture is quite low for our focal species, the level of change projected varied among seasons, with the least change expected during Dec–Feb and Sept–Nov, and the greatest change projected for Mar–May and June–Aug.

Altering the input for climate change scenario changed the assessment outcome for 13 (68.4 %) of the 19 species (Table 1). Not surprising, for most species, vulnerability

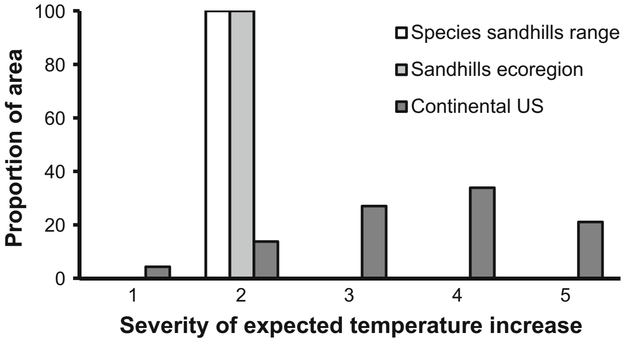

Fig. 4 Severity of temperature change expected by 2050 for species' distributions within assessment area (*white bars*), Sand Hills ecoregion (*light gray bars*), and the continental US (*dark gray bars*) based on the "ensemble" climate projections and medium emissions scenario. Severity categories are as follows: $1 \leq 3.9$°F; $2 = 3.9$–4.4°F; $3 = 4.5$–5°F; $4 = 5.1$–5.5°F; $5 \geq 5.5$°F

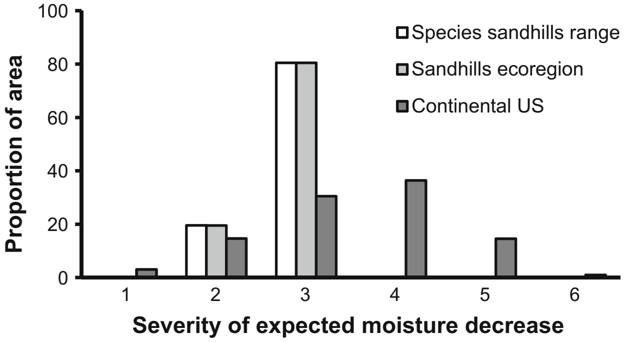

Fig. 5 Severity of moisture change (as measured by the Hamon AET:PET index) expected by 2050 for species' distributions within assessment area (*white bars*), Sand Hills ecoregion (*light gray bars*), and the continental US (*dark gray bars*) based on the "ensemble" climate projections and medium emissions scenario. Severity categories are as follows: $1 \geq -0.028$; $2 = -0.028$ to -0.050; $3 = -0.051$ to -0.073; $4 = -0.074$ to -0.096; $5 = -0.097$ to -0.119; $6 \leq -0.0119$, where negative values denote drying

was projected to increase with either higher projected emissions or more severe climate scenarios. Less severe projected emissions or climate changed reduced vulnerability ranks in six species, but only one shifted to "presumed stable." No species were ranked as "increase likely" under any climate or emissions scenario. Species that exhibited consistent ranks across scenarios tended to be those predicted to be either "extremely vulnerable" or "presumed stable" across all scenario combinations.

Geographic range sizes of sandhill species ranged from 20,335 to over 11.5 million km^2, but generally only a small portion of their ranges overlapped with the assessment area (2.27 ± 0.24 %; Table 2). Amphibians tended to have a higher proportion of overlap than did reptiles (3.13 ± 0.47 vs. 1.61 ± 0.61 %). Only two species had at least 10 % of their range occurring within the Sand Hills—pine barrens

Table 1 Effects of emissions scenario (High A2, Medium A1B, Low B1) and general circulation model (GCM; ensemble highest, ensemble average, ensemble lowest) on the NatureServe Climate Change Vulnerability Index rank for a subset of 19 species of reptiles and amphibians from the Sand Hills ecoregion of the southeastern US

Species	High A2			Medium A1B			Low B1		
	Ensemble highest	Ensemble average	Ensemble lowest	Ensemble highest	Ensemble average	Ensemble lowest	Ensemble highest	Ensemble average	Ensemble lowest
Anurans									
Anaxyrus quercicus									
Oak toad	EV	EV	HV	EV	EV	HV	EV	HV	HV
Lithobates capito									
Gopher frog	EV	HV	HV	EV	HV	HV	HV	HV	HV
Scaphiopus holbrookii									
Eastern spadefoot toad	EV	HV	HV	EV	HV	HV	HV	HV	HV
Salamanders									
Ambystoma talpoideum									
Mole salamander	EV	HV	HV	EV	HV	HV	HV	HV	HV
Ambystoma tigrinum									
Eastern tiger salamander	EV	HV	MV	EV	HV	MV	HV	MV	MV
Desmognathus apalachicolae									
Apalachicola dusky salamander	EV	EV	EV	EV	EV	EV	EV	EV	EV
Eurycea chamberlaini									
Chamberlain's dwarf salamander	HV	HV	HV	HV	HV	HV	HV	HV	HV
Notophthalmus viridescens									
Red spotted newt	MV	MV	PS	HV	MV	PS	MV	PS	PS
Turtles									
Deirochelys reticularia									
Chicken turtle	EV	HV	MV	EV	HV	MV	HV	MV	MV
Graptemys barbouri									
Barbour's map turtle	EV	EV	HV	EV	EV	HV	EV	HV	HV
Sternotherus odoratus									
Common musk turtle	HV	MV	MV	HV	MV	MV	MV	MV	MV
Terrapene carolina									
Eastern box turtle	HV	MV	MV	HV	MV	MV	MV	MV	MV
Snakes									
Coluber constrictor									
Black racer	PS	PS	PS	PS	PS	PS	PS	PS	PS
Elaphe obsoleta									
Rat snake	PS	PS	PS	PS	PS	PS	PS	PS	PS
Pituophis melanoleucus									
Pine snake	HV	MV	MV	EV	MV	MV	MV	MV	MV
Rhadinea flavilata									
Pine woods snake	EV	HV	MV	EV	HV	MV	HV	MV	MV
Seminatrix pygaea									
Black swamp snake	EV	EV	EV	EV	EV	EV	EV	EV	EV

Table 1 continued

Species	High A2			Medium A1B			Low B1		
	Ensemble highest	Ensemble average	Ensemble lowest	Ensemble highest	Ensemble average	Ensemble lowest	Ensemble highest	Ensemble average	Ensemble lowest
Lizards/crocodilians									
Anolis carolinensis									
Green anole	PS	PS	PS	PS	PS	PS	PS	PS	PS
Aspidoscelis sexlineata									
Six-lined racerunner	MV	PS	PS	MV	PS	PS	PS	PS	PS

The default combination recommended by the accompanying manual (Young et al. 2011a, b) is the Medium A1B emissions scenario and the ensemble average of 16 GCMs

tree frog (*H. andersonii*; 11.7 %) and Chamberlain's dwarf salamander (*Eurycea chamberlaini*; 18.8 %). When we used the entire geographic range versus only the range within the assessment area to score historic thermal and hydrologic niches, CCVI ranks remained unchanged for eight (42.1 %) species. For 10 species (52.6 %), the vulnerability rank decreased by one level (e.g., "highly vulnerable" to "moderately vulnerable"; Table 2). Only the eastern tiger salamander's (*Ambystoma tigrinum*) vulnerability ranking decreased by two levels—from "highly vulnerable" to "presumed stable". The number of species ranked as "presumed stable" increased from four to nine when considering their entire range.

We identified eight factors not explicitly considered in the NatureServe CCVI guidance documentation but which we suspect would either exacerbate or mitigate vulnerability of reptiles and amphibians to climate change. Both diel and seasonal activity patterns varied across taxa (Table 3). Lizards and crocodilians (91.7 %), and to a lesser extent turtles (56.3 %), were dominated by species that were strictly diurnal, whereas salamanders (72.7 %) were predominantly nocturnal. A surprising proportion of snake (44.7 %) and anuran (34.5 %) species could be active at either day or night, with the ability to alter their diel activity (Table 3). Within each taxonomic group, a higher proportion of species exhibited dormancy in response to cold temperatures than to dry or hot conditions. More amphibians than reptiles were classified as having dormancy in response to hot, dry conditions (Table 3). In most taxonomic groups, it was common for species to be fossorial or make use of underground retreats to escape unfavorable environmental conditions.

Reproductive mode varied strongly along taxonomic lines, with all amphibians depositing gelatinous eggs (either aquatically or terrestrially) that are more prone to desiccation than the calcified or shelled eggs characteristic of all lizards, crocodilians and turtles in our assessment area. Half of the snake species also laid shelled eggs, with the other half giving birth to live young (Table 3). Oviposition or parturition tended to occur over a 2.5–3.5 month period for all taxa except anurans, which had a mean oviposition period of 6.2 months. During this reproductive period, a large proportion of turtle species (87.5 %) and some anurans (17.2 %), snakes (7.9 %), and lizards and crocodilians (25.0 %) can produce more than one clutch. The combined egg and larval stages of salamanders (20.5 months) is almost ten times that of anurans. Finally, almost all turtle species, as well as the American alligator (*Alligator mississippiensis*), exhibit temperature-dependent sex determination (Table 3).

Discussion

We used the NatureServe CCVI to evaluate climate change vulnerability for a large suite of southeastern US reptile and amphibian species. We found the CCVI to be relatively easy to apply, facilitating rapid assessment of a large number of species, which can serve as a basis for subsequent prioritizations. A key benefit of the CCVI was the option to calculate many of the input variables using spatially explicit GIS data, which allowed a more quantitative and objective analysis of climate and landscape variables within the assessment area. Much of the data needed were available through NatureServe Explorer, including most species ranges, temperature, and precipitation maps. All other data were accessible either through standard primarily literature searches or by following links provided in the NatureServe Guidelines. Although collectively species ranked as having lower conservation risk to existing stressors were also generally less likely to be ranked as vulnerable to climate change, similar to Young et al. (2011b), we found that conservation rank could not be used as a proxy for predicting relative climate change vulnerability in individual species. However, as has been noted with previous CCVI assessments, we did find that the

Table 2 Comparison of the NatureServe Climate Change Vulnerability Index ranks resulting for a subset of 19 species of amphibians and reptiles from Sand Hills ecoregion of the southeastern US, when using the entire geographic range (range-modified rank) rather than the range within the assessment area (original rank) to calculate historical hydrologic and thermal niches

Species	Geographic range size (km^2)	% of range in assessment area	Original rank	Range-modified rank
Anurans				
Anaxyrus quercicus				
Oak toad	450,930	3.94	EV	HV
Lithobates capito				
Gopher frog	352,033	4.41	HV	HV
Scaphiopus holbrookii				
Eastern spadefoot toad	1,122,190	1.82	HV	MV
Salamanders				
Ambystoma talpoideum				
Mole salamander	678,160	2.01	HV	MV
Ambystoma tigrinum				
Eastern tiger salamander	5,148,910	0.15	HV	PS
Desmognathus apalachicolae				
Apalachicola dusky salamander	20,335	2.82	EV	EV
Eurycea chamberlaini				
Chamberlain's dwarf salamander	27,444	18.75	HV	MV
Notophthalmus viridescens				
Red spotted newt	3,440,360	0.55	MV	PS
Turtles				
Deirochelys reticularia				
Chicken turtle	908,674	1.05	HV	MV
Graptemys barbouri				
Barbour's map turtle	31,019	7.69	EV	HV
Sternotherus odoratus				
Common musk turtle	2,405,820	0.84	MV	PS
Terrapene carolina				
Eastern box turtle	1,276,380	1.55	MV	PS
Snakes				
Coluber constrictor				
Black racer	5,645,938	0.34	PS	PS
Elaphe obsoleta				
Rat snake	2,985,911	0.67	PS	PS
Pituophis melanoleucus				
Pine snake	556,168	3.63	MV	PS
Rhadinea flavilata				
Pine woods snake	181,522	3.02	HV	HV
Seminatrix pygaea				
Black swamp snake	241,631	3.74	EV	EV
Lizards/crocodilians				
Anolis carolinensis				
Green anole	1,182,017	1.78	PS	PS
Aspidoscelis sexlineata				
Six-lined racerunner	2,757,712	0.73	PS	PS

For each species, the size of entire geographic range and the percentage of its range occurring within the assessment area are listed

Table 3 Ecological traits commonly exhibited by reptiles and amphibians and that need to be considered when scoring sensitivity factors as part of the NatureServe Climate Change Vulnerability Index

Ecological traits	Effect on vulnerability	Anurans	Salamanders	Turtles	Snakes	Lizards and crocodilians	Relevant sensitivity factor(s)
Activity and behavior							
Diel activity							Physiological thermal niche
Strictly/primarily diurnal	↑	6.9 %	0.0 %	56.3 %	28.9 %	91.7 %	
Strictly/primarily nocturnal	↓	37.9 %	72.7 %	12.5 %	21.1 %	0.0 %	
Can be active day or night	↓	34.5 %	9.1 %	12.5 %	44.7 %	8.3 %	
Seasonal activity							Physiological thermal niche Physiological hydrological niche
Winter dormancy	↑	65.5 %	36.4 %	50.0 %	100.0 %	33.3 %	
Summer/drought dormancy	↓	41.4 %	31.8 %	25.0 %	13.2 %	0.0 %	
Fossorial/underground retreats	↓	27.6 %	59.1 %	6.3 %	65.8 %	41.7 %	Physiological thermal niche
Reproduction and development							
Reproductive mode							Physiological thermal niche Physiological hydrological niche
Lays gelatinous eggs	↑	100.0 %	100.0 %	0.0 %	0.0 %	0.0 %	
Lays calcified/shelled eggs	↓	0.0 %	0.0 %	100.0 %	50.0 %	100.0 %	
Live birth	↓	0.0 %	0.0 %	0.0 %	50.0 %	0.0 %	
Length of oviposition/parturition period (months)	−	6.2 months	3.4 months	2.9 months	2.7 months	2.7 months	Physiological hydrological niche Physiological thermal niche
Can have multiple clutches	↓	17.2 %	0.0 %	87.5 %	7.9 %	25.0 %	Physiological thermal niche Physiological hydrological niche
Length of egg/larval period	+	2.4 months	20.5 months	N/A	N/A	N/A	Physiological hydrologic niche
Has TSD	+	N/A	N/A	93.8 %	0.0 %	8.3 %	Physiological thermal niche

Each species within the Sand Hills ecoregion assessment area was evaluated with regard to each trait, and the traits are summarized by taxa with percentages corresponding to the percent of species exhibiting the trait. Duration of oviposition/parturition period and egg/larval period (amphibians only) are reported in number of months (mo). TSD = temperature dependent sex determination. Presumed effect on vulnerability is listed as follows: ↑increase vulnerability, ↓ decrease vulnerability, + vulnerability positively correlated, − vulnerability negatively correlated selection of input parameters can strongly influence CCVI ranks (e.g., Sperry and Hayden 2011). In addition, we found that some ecological traits common in, but relatively unique to, reptiles and amphibians may require special consideration when scoring sensitivity factors in order to adequately characterize a species' vulnerability to climate change.

Although not an issue specific to reptiles and amphibians, we found that whether we used a species' entire geographic range or just its range in the assessment area when scoring historical thermal and hydrologic niches, strongly influenced CCVI rank. The NatureServe guidelines (Young et al. 2011a) instruct the user to score these sensitivity factors based on annual precipitation or temperature variation in the species' range within the assessment area. At a small spatial scale, climatic variation across the assessment area can be very low, often leading to a classification of high vulnerability. However, variability across the broader geographic range of the species is often much higher and, we think, likely reflects the true climatic variation that a species has experienced and thus may better predict its adaptive capacity (sensu Williams et al. 2008). Using the full geographic range would minimize artificial inflation of perceived vulnerability stemming from small assessment area size, particularly when (as in our case) only a small proportion of a species' range overlaps with the assessment area. Even though our assessment area was at the relatively large scale of an ecoregion, we found that quantifying past exposure based on species' full geographic range reduced the vulnerability ranks of more than half of the species. Using this approach also changed the relative vulnerability ranks among species, potentially influencing how some species might be subsequently prioritized for conservation action.

Choice of climate model and emissions scenarios also influenced CCVI rank. The outputs of climate models are a source of uncertainty universal to all climate assessment approaches (Rowland et al. 2011). Multiple factors contribute to their uncertainty (see Rowland et al. 2011 and references therein), including most fundamentally, how the underlying algorithms and parameters vary among models. The default option in NatureServe is to use the medium emissions scenario and the ensemble climate model, which represents a median of the 16 primary global circulation models (Young et al. 2011a). However, the user has wide latitude in selecting the climate model or emissions scenarios, depending on the relative suitability of specific models to the assessment area and on whether the user is interested in the "worst case," "average" or "best case" scenario. If climate uncertainty is a concern, one potential option is to identify species with consistent vulnerability ranks across model scenarios. For example, in our analyses, the ratsnake, black racer and green anole (*Anolis carolinensis*) were consistently ranked as "presumed stable," increasing our confidence that they are relatively secure from the threats of climate change. At the other extreme, the Apalachicola dusky salamander (*Desmognathus apalachicolae*) and the black swamp snake (*Seminatrix pygaea*) were ranked "extremely vulnerable" regardless of scenario, providing strong evidence that they are species at high risk of climate-related impacts.

Of more concern, particularly for reptiles and amphibians, is that projected climate data rely on annual climatic averages, which may not adequately capture the climate variability species are likely to experience. For example, many reptile and amphibian species in the Sand Hills ecoregion are associated with isolated, ephemeral wetlands (Moler and Franz 1987; Semlitsch and Bodie 1998; Russell et al. 2002). Reproductive success and population persistence of individual species can be strongly influenced by the timing and amount of precipitation and associated effects on hydroperiod (Walls et al. 2013a, b). For many reptile and especially amphibian species, it may be important to focus on projected changes during a particular season (Young et al. 2011a), particularly those species with seasonal breeding cycles or that rely on seasonally available habitats. Species sensitivity or response to extreme climatic events can be captured by the physiological thermal and hydrologic niche factors. However, as has been noted in previous applications (Rowland et al. 2011; Sperry and Hayden 2011), CCVI does provide a means to predict species' exposure to an increase in climate variability or stochastic events, such as floods or droughts (Katz and Brown 1992; Paaijmans et al. 2013; Vasseur et al. 2014). Climate change is expected to increase average overall temperatures and the frequency of extreme summer temperatures, resulting in increased risk of heat stress to ectotherms, even in temperate climates (Hoffmann et al. 2013; Kingsolver et al. 2013; Gerick et al. 2014). Likewise, drought frequency, duration and severity are also predicted to increase (Kundzewicz et al. 2008). Although pond-breeding amphibians can skip reproduction in years when ponds are dry, consecutive years of recruitment failure due to extended drought could result in local extirpation of sensitive species (Westervelt et al. 2013). Thus, herpetofauna are likely to be particularly vulnerable to increased frequency and severity of extreme climate conditions, and this vulnerability may be underestimated by the CCVI rank. Future iterations of NatureServe's CCVI that explicitly incorporate species' exposure to extreme events would improve its suitability as an assessment tool for reptiles and amphibians.

Reptiles and amphibians possess a variety of physiological, ecological, and behavioral characteristics that may alter their sensitivity or their adaptive capacity to avoid, cope with, or recover from climate variability and its impacts (Kearney et al. 2009; Glick et al. 2011). Thus, special care should be taken when scoring sensitivity factors in order to fully capture these relationships. Most notably, the NatureServe guidelines instruct the user to score physiological thermal niche based on a species' dependence on cool or cold above-ground habitats, such as those occurring at high elevations or extreme latitudes (Young et al. 2011a). However, the challenge for most species in our assessment area is limiting exposure to extreme heat (Kearney et al. 2009; Hoffmann et al. 2013). A large proportion of species we evaluated are able to resist potential exposure, and presumably reduce their vulnerability, by aestivating (i.e., becoming dormant in response to hot or dry conditions), being fossorial or using underground retreats such as stump holes or burrows of other animals, or facultatively shifting their diel activity patterns between being diurnal and nocturnal. Taxa dominated by strictly diurnal species and species that do not aestivate or seek underground retreats (e.g., lizards) may be more vulnerable to climate change than indicated by their CCVI ranks and relatively more vulnerable to climate change than species that do not exhibit these traits (Kearney et al. 2009).

One potential solution is for the user to modify the final vulnerability rank to better reflect adaptive capacity of individual species. For example, species that are able to reduce or shift their activity in response to changing climate could be assigned the next lower vulnerability category than the one generated by CCVI. Young et al. (2011a) suggested a similar approach for accounting for effects of long generation times on adaptation capacity by assigning species the next highest vulnerability category. Another option is for the user to modify the relative weights assigned to sensitivity factors when applying the CCVI tool to a suite of species thought to be particularly sensitive to certain factors. This approach was identified as a potential user-implemented modification to CCVI when assessing vulnerability of Arctic birds (Liebezeit et al. 2012). Other solutions include modification of the scoring instructions or of the CCVI assessment tool itself. As more users have provided feedback regarding their experiences using the tool, the scoring instructions have been expanded to provide more guidance and examples on how to deal with specific species traits or habitat scenarios, such as aquatic species (Young et al. 2011a, 2015). Specific guidance on how to incorporate the ecological traits we identified (Table 3) would improve the tool's application to reptiles and amphibians. Finally, some traits, particularly fossorial habits or temperature-dependent sex determination, may warrant changes to the actual CCVI itself. The second version of CCVI changed the underlying rank calculations for cave-obligate and groundwater species to reflect the buffering capacity of their habitats (Young et al. 2011a). Future iterations of the CCVI should consider similar accommodations for fossorial species.

One of the biggest challenges we encountered was that very little information is available to document, model, or predict the response of reptiles and amphibians to climate change. Information on phenological shifts was available for only about a quarter of species we evaluated (e.g., Todd et al. 2011). However, easily quantified reproductive characteristics (Table 3), such as length of oviposition/parturition period, may serve as useful indicators of species' ability to change their breeding phenology. Specific guidance in the NatureServe manual on how these traits could be incorporated into the assessment process would be helpful. Likewise, model-based predictions of species distributions or population sizes under future climate scenarios were also lacking. However, for many reptile and amphibian species, there are available field or laboratory data that would be useful for estimating parameters in such models, such as activity temperatures (e.g., Avery 1982) and evaporative water loss rates (e.g., Mautz 1982). The power of the CCVI would be much enhanced if future iterations created a mechanism for making use of these data even though they have not been incorporated into formal climate-related vulnerability models.

Conclusions

Despite these concerns, the NatureServe CCVI was a useful tool for screening large numbers of reptile and amphibian species. One of our most important findings was that, although the CCVI has been used to evaluate a wide variety of taxa, some characteristics that are common but unique to reptiles and amphibians may influence how closely a species' vulnerability rank reflects its sensitivity and adaptive capacity. Most of these unique traits could be addressed through improved guidance to the user as to how to explicitly consider these traits when scoring sensitivity factors or through relatively minor modifications to the assessment tool itself. Alternatively, the user has wide flexibility in modifying the final CCVI ranks or the way individual sensitivity factors are scored to capture the full range of factors influencing their vulnerability, although this approach may complicate comparing ranks with other taxonomic groups. Sensitivity analyses proved to be an important component of the assessment process and can be used to examine the effects of uncertainty with regard to climate change projections or parameter values, or to accommodate differing levels of risk tolerance, allowing the user to adjust parameter scores or select climate maps to evaluate vulnerability under "best case," "worst case," or "average case" scenarios (Rowland et al. 2011; Young et al. 2015). In short, the user can design a suite of analyses or manipulations to vulnerability ranks that can be used to interpret NatureServe results, evaluate how much confidence to place in vulnerability ranks based on the particular sources of uncertainty, and how to best incorporate assessment results into natural resource planning.

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Ethical standards The work conducted here complies with current laws of the country in which it was performed.

Conflict of interest The authors declare that they have no conflict of interest.

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