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Journal
Conservation Biology, 30(6)

ISSN
0888-8892

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Publication Date
2016-12-01

DOI
10.1111/cobi.12686

Peer reviewed

Conservation Biology

Contributed Paper

Using citizen science data to identify the sensitivity of species to human land use

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Abstract: *Conservation practitioners must contend with an increasing array of threats that affect biodiversity. Citizen scientists can provide timely and expansive information for addressing these threats across large scales, but their data may contain sampling biases. We used randomization procedures to account for possible sampling biases in opportunistically reported citizen science data to identify species' sensitivities to human land use. We analyzed 21,044 records of 143 native reptile and amphibian species reported to the Carolina Herp Atlas from North Carolina and South Carolina between 1 January 1990 and 12 July 2014. Sensitive species significantly associated with natural landscapes were 3.4 times more likely to be legally protected or treated as of conservation concern by state resource agencies than less sensitive species significantly associated with human-dominated landscapes. Many of the species significantly associated with natural landscapes occurred primarily in habitats that had been nearly eradicated or otherwise altered in the Carolinas, including isolated wetlands, longleaf pine savannas, and Appalachian forests. Rare species with few reports were more likely to be associated with natural landscapes and 3.2 times more likely to be legally protected or treated as of conservation concern than species with at least 20 reported occurrences. Our results suggest that opportunistically reported citizen science data can be used to identify sensitive species and that species currently restricted primarily to natural landscapes are likely at greatest risk of decline from future losses of natural habitat. Our approach demonstrates the usefulness of citizen science data in prioritizing conservation and in helping practitioners address species declines and extinctions at large extents.*

Keywords: amphibian, assessments, biodiversity, habitat loss, outreach, public education, reptile

Utilización de Datos de Ciencia Ciudadana para Identificar la Sensibilidad de las Especies al Uso Humano del Suelo

Resumen: *Quienes practican la conservación deben enfrentarse a un despliegue creciente de amenazas que afectan a la biodiversidad. La ciencia ciudadana puede proporcionar información oportuna y expansiva para encarar a estas amenazas a grandes escalas, pero sus datos pueden contener sesgos de muestreo. Usamos procedimientos aleatorios para representar los posibles sesgos de muestreo en datos de ciencia ciudadana reportados de manera oportuna para identificar la sensibilidad de las especies al uso humano del suelo. Analizamos 21,044 registros de 143 especies de anfibios y reptiles nativas de Carolina del Norte y Carolina del Sur de reportadas al Carolina Herp Atlas entre enero 1 de 1990 y el 12 de julio de 2004. Las especies sensibles asociadas significativamente con paisajes naturales tuvieron 3.4 veces más probabilidad de ser protegidas legalmente o tratadas como de importancia para la conservación por las agencias estatales de recursos que especies menos sensibles asociadas significativamente con los paisajes dominados por humanos. Muchas de las especies asociadas significativamente con los paisajes naturales ocurrían principalmente en los hábitats que habían sido casi erradicados o alterados de otra forma en las Carolinas, incluyendo los humedales aislados, las sabanas de pinos de hoja larga y los bosques de los Apalaches. Las especies raras con pocos reportes tuvieron una mayor probabilidad de ser asociadas con paisajes naturales y 3.2 veces más probabilidad de ser protegidas legalmente o tratadas como de importancia para la conservación que las especies con al menos 20 ocurrencias reportadas. Nuestros resultados sugieren que los datos de ciencia ciudadana reportados de*

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Paper submitted October 13, 2015; revised manuscript accepted February 5, 2016.

DOI: 10.1111/cobi.12686

manera oportuna pueden usarse para identificar especies sensibles y que las especies que actualmente están restringidas principalmente a los paisajes naturales tienen un mayor riesgo de declinar a partir de futuras pérdidas del hábitat natural. Nuestra estrategia demuestra la utilidad de los datos de ciencia ciudadana en la priorización de la conservación y en el apoyo a quienes practican la conservación para tratar las declinaciones y las extinciones con un mayor alcance.

Palabras Clave: alcance, anfibio, biodiversidad, educación pública, pérdida de hábitat, reptil

Introduction

Conservation practitioners must contend with an increasing array of anthropogenic threats to biodiversity. Many of these threats, such as climate change and land conversion, affect numerous species and occur at large scales (Sala et al. 2000). The scale of these impacts poses a formidable challenge for predicting and understanding how species will respond and for determining when, where, and how to direct management. Addressing these issues may require data sets of species distributions across broad spatial and temporal scales. Such large data sets are difficult to obtain, a prospect made even more challenging given declining funding for conservation (Heinz Center 2008; Meretsky et al. 2012). Hence, there is great interest in finding ways to leverage public involvement in collecting data for conservation (Cohn 2008).

The use of citizen scientists—usually unpaid members of the public—to collect data has become a popular method of obtaining spatially and temporally expansive data sets such as biodiversity atlases (Devictor et al. 2010). Atlases are often data sets of species occurrences collected by members of the public and submitted to a coordinated repository (Robertson et al. 2010) and have long been used for purposes such as biodiversity assessments (Donald & Fuller 1998). However, data from atlas projects are now being used to provide key insights into how contemporary threats shape biodiversity. For example, atlas data are used to project changes in species distributions related to climate change (Maggini et al. 2014), to examine trends in species occupancy over time (Kery et al. 2009), and to predict invasions by non-native species to anticipate management problems (Rose & Todd 2014). One primary benefit of atlas data collected by citizen scientists is the immediacy with which data can be accumulated online, which facilitates addressing contemporary conservation challenges (Sullivan et al. 2009; Hobern et al. 2014).

The most pervasive threat to biodiversity is habitat loss (Sala et al. 2000). Habitat loss, however, affects species differently, depending on how sensitive they are to human land use (Henle et al. 2004). Sensitive species avoid highly altered landscapes in favor of natural areas (McKinney 2006), and these species are often at greatest risk of decline from loss of natural habitat. In contrast, less-sensitive species may remain common in human-dominated landscapes—defined by Theobald (2010) as areas converted from natural land cover to urban or built areas, agricultural areas, and roads—possibly because they benefit from resource subsidies or other opportunities provided in areas of high human land use (McKinney 2006). Identifying the extent to which species are distributed among natural or human-dominated landscapes may greatly aid conservation assessments by revealing which species are at greatest risk of habitat loss from land-use change (Broms et al. 2014). Evaluating how these species are distributed is made more feasible with large data sets like those generated by citizen science atlases.

We sought to evaluate how well citizen science data can be used to identify species that occur predominantly in natural areas (sensitive species) and species that occur predominantly in human-dominated areas (less-sensitive species). Opportunistically reported citizen science data can present challenges for data analysis (Devictor et al. 2010; Dickinson et al. 2010), and addressing such limitations could allow citizen scientists to better contribute to conservation and biodiversity assessments (Higa et al. 2015). We used randomization procedures to address possible spatial, effort-based, or detection biases to generate comparisons of species' distributions across a land-use gradient. This allowed us to classify species into one of 3 groups: those more often associated with natural landscapes, those more often associated with human-dominated landscapes, and those with no significant landscape association. We expected species associated with natural landscapes to have declined because of habitat loss. Thus, we expected species of conservation concern or those protected by law to be more associated with natural landscapes than with human-dominated landscapes or to have no significant landscape association.

Methods

Citizen Science Data

We obtained occurrences of amphibians and reptiles from a citizen science monitoring project, the Carolina Herp Atlas (CHA) (www.carolinaherpatlas.org), which uses the internet to collect, archive, display, and share occurrence records for amphibians and reptiles and allows users to maintain a personal database of observations. The CHA requires users to submit scientific and common names of species, date of observation, state and county of observation, and a precise (within 5 m), georeferenced locality with each record. Users are encouraged to submit a digital image voucher for each observation and to provide additional comments about each observation (i.e., description, behavior, habitat information, etc.). To ease submission of observations and reduce errors, the CHA includes drop-down menus for scientific names, common names, counties, and date, instructions for locality description, and online references to aid in species' identification. The CHA also includes an integrated geomapper that allows users to identify precisely where each submitted observation was made; the georeferenced coordinates are automatically appended to each observation. Each submitted observation is reviewed (and potentially edited) by staff at Davidson College to ensure accuracy. After review, each record is assigned a status code to reflect its accuracy. Records with accompanying digital images are categorized as verified. Records that do not include a digital image but otherwise appear to be accurate are categorized as credible. Potentially erroneous records, such as observations outside of a species' known distribution, mismatched county designation and georeferenced location, or a description of the organism that does not match the species selected, are categorized as not credible unless follow-up consultation with the submitter clarifies ambiguities (e.g., providing a digital image or correcting submission errors). See Price and Dorcas (2011) for more information on the CHA.

Statistical Analyses

We used only CHA records categorized as verified or credible and dated from 1 January 1990 to 12 July 2014. We did not use data older than 1990 because our land-use data were more recent (see below). We excluded American alligators (*Alligator mississippiensis*), sea turtles, 3 non-native lizard species, and fully aquatic, obligately paedomorphic salamander species because these species are either rarely encountered incidentally or they are not generally found via the types of search effort used by most contributors to find the remaining species (e.g., active terrestrial searching, use of coverboards, turning cover objects, driving roads at night). This left 21,044 occurrence records, representing 32 frog, 48 salamander, 10 lizard, 38 snake, and 15 turtle species.

We used the GIS layer of Theobald (2010) and ArcGIS 10.3 to characterize the degree of naturalness of the landscape for each CHA observation. Theobald (2010) used the 2001 National Land Cover Database to create the natural landscape (NL) metric. He categorized each 30-m cell of terrestrial landscape as having either human-dominated land cover (0) (urban or built, roads, or agricultural or cropland) or natural land cover (1) (forest, grass- or shrubland, or wetland or riparian). Theobald (2010) then converted this binary measure to a continuous scale with scores ranging from 0 to 1 at 270-m resolution by using an inverse distance-weighted nearest-neighbor approach that incorporated neighboring cells up to 109 km away from the focal cell. Thus, a cell whose entire neighborhood is natural land cover has an NL value of 1, a cell whose entire neighborhood is human-dominated land cover has an NL value of 0, and most 270-m cells have NL values between 0 and 1, depending on their land-cover type and that of neighboring cells. The proportion of cells that changed land-cover classification from natural to human dominated from 1992 to 2001 was <3.5% (Theobald 2010). Thus, we used the NL metric because it provides a reasonably contemporaneous approximation of human land use for examining the distribution of CHA observations from the period we analyzed.

Observations in the CHA represent voluntary reports of incidental encounters and encounters resulting from active search effort by contributors. There were no data reported from planned systematic surveys across North Carolina and South Carolina, so CHA observations may be subject to reporting biases both spatially and among taxa. For example, more observations are likely made from areas where human population densities are greater, and people appear more likely to report observations of snakes than those of other species (Price & Dorcas 2011). Such biases could produce erroneous conclusions about the relationship between species' distributions and environmental variables (Phillips et al. 2009) and thus must be addressed.

We used a bootstrapping approach to account for possible sampling biases in the data. We first extracted the NL value of each cell with a CHA occurrence. We then calculated the mean NL value of a species' occurrences and compared this value with bootstrapped mean NL values of 1000 random draws from all occurrences (including the focal species) in its taxon (frog, salamander, lizard, snake, or turtle) within the biogeographic range of the focal species, after removing spatially duplicated (overlapping) points. This method accounts for possible sampling bias in the CHA data by comparing the mean NL value of a species' occurrences with 1000 possible means where sampling effort was reported, thus accounting for the actual sampling process itself (Phillips et al. 2009). We calculated the mean NL value for each species with ≥20 occurrences in the CHA. We then calculated the mean NL value for each of 1000 bootstrapped samples equal in size to the number of observations of the focal species by using all occurrences in that taxon (including the focal species) that were located within 20 km of the biogeographic range of the focal species. Finally, we ordered the 1000 means of bootstrapped samples and used the 25th and 975th means to assess significance at the $\alpha = 0.05$ level (Lunneborg 2000). In this way, we examined how extreme the actual mean NL value for each focal species was compared with means of 1000 possible samples where the focal species could have been found and reported.

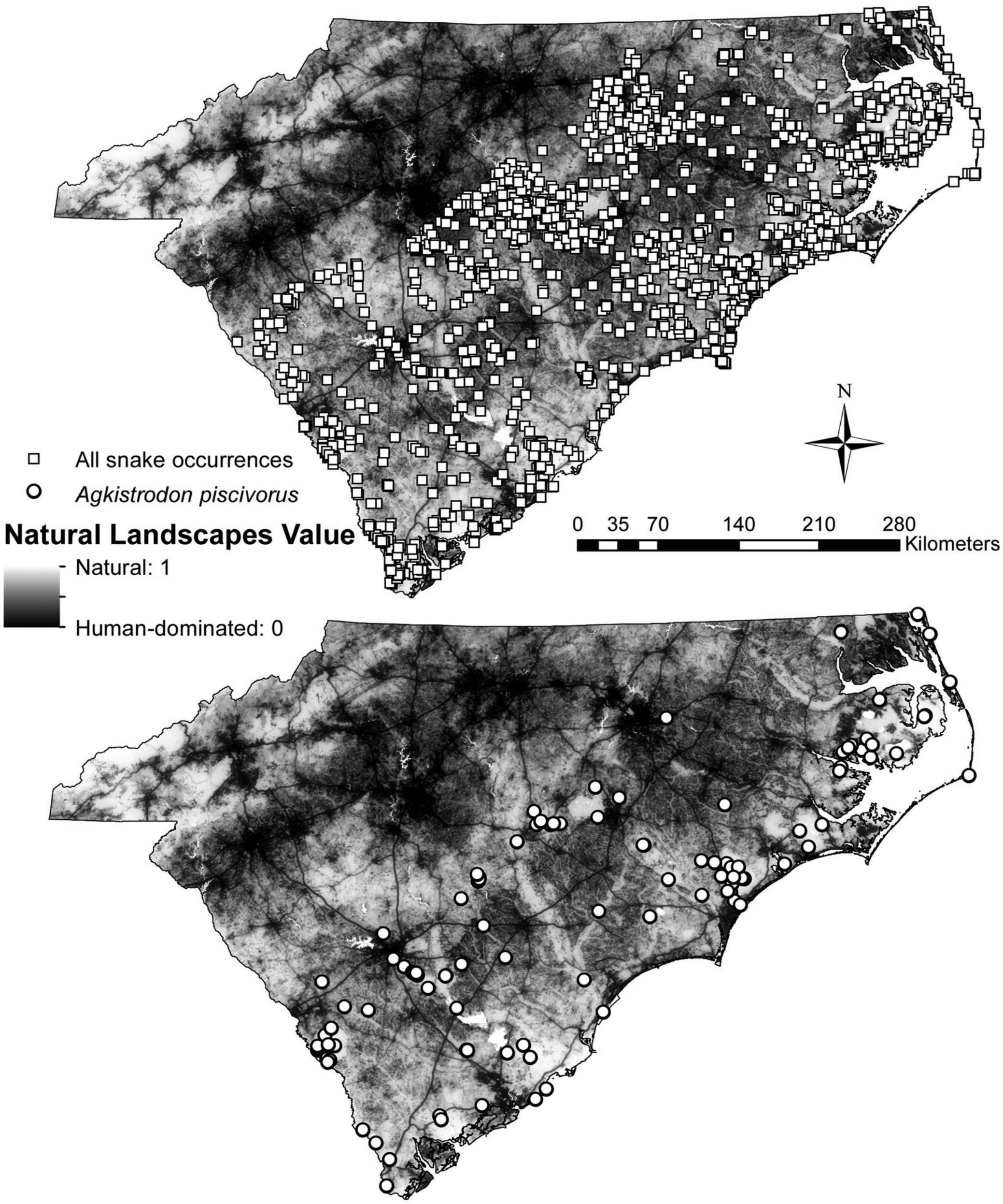

Figure 1. Natural landscapes geographic information system layer for North and South Carolina and all snake occurrences within 20 km of the biogeographic range of Agkistrodon piscivorus (top panel) and occurrences of only Agkistrodon piscivorus (bottom panel).

For example, there were 199 nonoverlapping observations of the cottonmouth snake (*Agkistrodon piscivorus*) in the CHA database (Fig. 1). First, we calculated the mean NL value from all nonoverlapping occurrences for this species. Within 20 km of the biogeographic range of *A. piscivorus* in North Carolina and South Carolina, there were 3144 nonoverlapping occurrences of all snakes, including *A. piscivorus* (Fig. 1). From these occurrences, we next drew 1000 samples of 199 occurrences with replacement and calculated the mean NL value for each bootstrapped sample. We ordered the 1000 bootstrapped means. If the actual mean NL value for *A. piscivorus* fell below the 25th bootstrapped mean NL value from all snake occurrences, we concluded that *A. piscivorus* occurred in significantly more human-dominated areas than the typical snake in its biogeographic range. If the actual mean NL for *A. piscivorus* was above the 975th bootstrapped mean NL value from all snake occurrences, we concluded *A. piscivorus* occurred in significantly more natural habitat than the typical snake in its biogeographic range.

We calculated effect sizes as a measure of the degree to which the mean NL value of each species exceeded or fell below the mean NL value of bootstrapped samples from all species occurrences in its taxon within its biogeographic range. We used the pooled standard deviation to calculate effect size as the difference between a species' actual mean NL value and the mean NL value of bootstrapped samples from all species occurrences for each bootstrapping iteration. We report the overall mean effect size from the 1000 bootstrapped iterations for each focal species.

We downloaded shapefiles of most species' ranges from the International Union for Conservation of Nature (IUCN) website (http://www.iucnredlist.org/) when available. For turtles, we relied on shapefiles generated at the watershed level provided by Buhlmann et al. (2009). In the few instances where shapefiles were not available, we scanned and digitized species' ranges from figures in field guides or scientific books to select background occurrence points as described above. The source of shapefiles for each species' range is in Supporting Information.

We queried the NatureServe database (http://explorer.natureserve.org/, accessed 6 March 2015) and recorded the NatureServe global, national, and state assessment status for each species as well as its IUCN assessment status and whether it was listed under the U.S. Endangered Species Act (ESA) (Supporting Information). Species assessments were recorded as of conservation concern when species were ranked as anything other than apparently secure or secure by NatureServe or anything other than least concern by IUCN. We also recorded whether each species was listed as threatened or endangered by North Carolina or South Carolina or treated by either state as a species of special concern (SSC) (North Carolina Wildlife Resources Commission 2014; South Carolina Department of Natural Resources Heritage Trust Program 2014) (Supporting Information).

There were 61 species for which <20 nonoverlapping occurrences were reported; thus, we did not analyze these species individually. (See Supporting Information for sample sizes.) We grouped occurrences of these rare species within each taxon. For each taxon with ≥20 total nonoverlapping occurrences of rare species, we compared their collective distribution with those of all observations from within 20 km of the concatenated range of all rare species in that taxon. This allowed us to determine whether rare species as a whole were reported from more or less natural landscapes than other species in their taxon based on the bootstrapping procedure described above. We were unable to use this approach for lizards because there were only 7 occurrences of 2 species that could not be analyzed.

We conducted spatial analyses in ArcGIS 10.3 and used R (version 3.1.2, R Foundation for Statistical Computing) for bootstrapping procedures. We used Fisher's exact tests in R to compare the conservation status of species found in significantly more natural landscapes, those found in significantly more human-dominated landscapes, and those with no significant land associations. Finally, we used a Fisher's exact test in R to compare the conservation status of species with <20 occurrences in the CHA with those with ≥20 occurrences.

Results

At least 20 verified or credible georeferenced nonoverlapping occurrences were available for the majority of native amphibians and reptiles that occur in the Carolinas. However, 31% of frogs, 34% of salamanders (excluding entirely aquatic species), 33% of lizards (excluding 3 nonnative species), 13% of snakes, and 41% of turtles (excluding sea turtles) had <20 occurrences, and thus were not analyzed at the species level (Supporting Information).

For each of the 5 taxa, species fell along a continuum from those reported in more natural landscapes to those reported in more human-dominated landscapes than other species in their taxonomic group. Using the results of the bootstrapping analyses, we thus classified species into one of 3 groups along this continuum: significantly associated with natural areas, no significant landscape association, and significantly associated with human land use.

Among the frogs, 7 species were significantly associated with natural areas, 4 were significantly associated with human land use, and the remaining 11 species had no significant landscape associations (Table 1). For salamanders 4 species were significantly associated with natural areas, 3 were significantly associated with human land use, and the remaining 11 species had no significant landscape associations (Table 2). For lizards 2 species were significantly associated with natural areas, whereas the remaining 6 species had no significant landscape associations (Table 3). For snakes 12 species were significantly associated with natural areas, 9 were significantly associated with human land use, and the remaining 12 species had no significant landscape associations (Table 4). Finally, among turtles, 3 species were significantly associated with natural areas, 3 were significantly associated with human land use, and the remaining 4 species had no significant landscape associations (Table 5).

Of the 91 species analyzed, 39.3% of species associated with natural areas warranted conservation concern (based on IUCN and NatureServe assessments) or were legally protected (ESA or state protected and SSC), compared with 21.1% of species associated with human land use and 20.5% of species with no significant landscape association. This difference in conservation status among the 3 groups was not significant ($\chi^2 = 3.5$, df $= 2$, $p = 0.18$). However, of the 91 species analyzed, 35.7% of species associated with natural areas were legally protected or were treated by a state as a species of special concern, compared with 10.5% of species associated with human land use and 15.9% of species with no signifi-

Table 1. Conservation and statutory status of frog species ordered by effect size based on the mean natural landscape value of their occurrences and 95% confidence intervals of means from 1000 bootstrapped samples of all frogs within the species' biogeographic range.

Species	*Effect size*[a]	*Status*[b]	*Mean*	*95% CIs*
Hyla femoralis[c]	0.75		0.706	0.524–0.624
Lithobates virgatipes[c]	0.72		0.734	0.545–0.677
Acris gryllus[c]	0.61		0.692	0.547–0.616
Hyla gratiosa[c]	0.56		0.688	0.511–0.654
Pseudacris ocularis	0.45		0.693	0.523–0.693
Lithobates sylvaticus[c]	0.34	C,P	0.528	0.406–0.522
Lithobates sphenocephalus[c]	0.28		0.582	0.493–0.553
Lithobates clamitans[c]	0.26		0.577	0.493–0.551
Hyla squirella	0.21		0.597	0.499–0.602
Gastrophryne carolinensis	0.15		0.560	0.485–0.571
Hyla cinerea	0.14		0.614	0.545–0.619
Acris crepitans	0.13	C,P	0.542	0.486–0.546
Pseudacris crucifer	0.03		0.528	0.496–0.548
Hyla chrysoscelis	0.03		0.531	0.492–0.550
Lithobates catesbeianus	0.00		0.522	0.493–0.548
Anaxyrus americanus	−0.06		0.451	0.429–0.494
Pseudacris brimleyi	−0.08		0.599	0.520–0.693
Anaxyrus terrestris	−0.11		0.589	0.565–0.649
Anaxyrus fowleri[d]	−0.17		0.482	0.486–0.542
Pseudacris feriarum[d]	−0.21		0.458	0.466–0.524
Lithobates palustris[d]	−0.29	C,P	0.464	0.477–0.568
Scaphiopus holbrookii[d]	−0.40		0.449	0.451–0.605

[a]Positive numbers indicate a species was found in more natural landscapes than expected based on bootstrapped samples and negative numbers indicate a species was found in more human-dominated landscapes than expected based on bootstrapped samples.
[b]Abbreviations: C, species with conservation status of anything other than apparently secure or secure as assigned by NatureServe or anything other than least concern as assigned by International Union for Conservation of Nature; P, protected species listed as endangered or threatened by federal or state statutes or listed as a species of special concern by North Carolina or South Carolina natural resource agencies.
[c]Species significantly associated with natural landscapes.
[d]Species significantly associated with human-dominated landscapes.

Table 2. Conservation and statutory status of salamander species ordered by effect size based on the mean natural landscape value of their occurrences and 95% confidence intervals of means from 1000 bootstrapped samples of all salamanders within the species' biogeographic range.

Species	*Effect size*[a]	*Status*[b]	*Mean*	*95% CIs*
Desmognathus quadramaculatus[c]	0.61		0.679	0.515–0.621
Ambystoma talpoideum[c]	0.50	C,P	0.722	0.556–0.714
Aneides aeneus[c]	0.43	C,P	0.720	0.590–0.714
Gyrinophilus porphyriticus[c]	0.39		0.636	0.486–0.632
Pseudotriton ruber	0.24		0.601	0.504–0.603
Desmognathus ocoee	0.19	C	0.702	0.616–0.714
Notophthalmus viridescens	0.19		0.600	0.523–0.603
Pseudotriton montanus	0.16	C,P	0.591	0.468–0.649
Eurycea guttolineata	0.10		0.584	0.504–0.622
Desmognathus monticola	0.09		0.650	0.586–0.677
Eurycea wilderae	0.01		0.635	0.571–0.688
Plethodon cinereus	0.00		0.571	0.496–0.654
Ambystoma opacum	−0.04		0.556	0.527–0.598
Plethodon chlorobryonis	−0.07		0.674	0.641–0.727
Ambystoma maculatum	−0.08		0.548	0.523–0.603
Plethodon cylindraceus[d]	−0.21		0.489	0.491–0.561
Eurycea cirrigera[d]	−0.42		0.473	0.527–0.598
Desmognathus fuscus[d]	−0.53		0.438	0.514–0.584

[a]Positive numbers indicate a species was found in more natural landscapes than expected based on bootstrapped samples and negative numbers indicate a species was found in more human-dominated landscapes than expected based on bootstrapped samples.
[b]Abbreviations: C, species with conservation status of anything other than apparently secure or secure as assigned by NatureServe or anything other than least concern as assigned by International Union for Conservation of Nature; P, protected species listed as endangered or threatened by federal or state statutes or listed as a species of special concern by North Carolina or South Carolina natural resource agencies.
[c]Species significantly associated with natural landscapes.
[d]Species significantly associated with human-dominated landscapes.

Table 3. Conservation and statutory status of lizard species ordered by effect size based on the mean natural landscape value of their occurrences and 95% confidence intervals of means from 1000 bootstrapped samples of all lizards within the species' biogeographic range.

Species	*Effect size*[a]	*Status*[b]	*Mean*	*95% CIs*
Aspidoscelis sexlineata[c]	0.46		0.622	0.496–0.581
Plestiodon inexpectatus[c]	0.31		0.595	0.496–0.575
Plestiodon laticeps	0.21		0.580	0.488–0.590
Scincella lateralis	0.14		0.565	0.510–0.566
Anolis carolinensis	0.10		0.556	0.509–0.560
Sceloporus undulatus	0.00		0.536	0.509–0.562
Plestiodon fasciatus	−0.03		0.533	0.504–0.570
Ophisaurus ventralis	−0.28		0.553	0.544–0.651

[a]Positive numbers indicate a species was found in more natural landscapes than expected based on bootstrapped samples and negative numbers indicate a species was found in more human-dominated landscapes than expected based on bootstrapped samples.
[b]Abbreviations: C, species with conservation status of anything other than apparently secure or secure as assigned by NatureServe or anything other than least concern as assigned by International Union for Conservation of Nature; P, protected species listed as endangered or threatened by federal or state statutes or listed as a species of special concern by North Carolina or South Carolina natural resource agencies.
[c]Species significantly associated with natural landscapes.

Table 4. Conservation and statutory status of snake species ordered by effect size based on the mean natural landscape value of their occurrences and 95% confidence intervals of means from 1000 bootstrapped samples of all snakes within the species' biogeographic range.

Species	*Effect size*[a]	*Status*[b]	*Mean*	*95% CIs*
Seminatrix pygaea[c]	1.00	C,P	0.846	0.681–0.759
Nerodia taxispilota[c]	0.78		0.735	0.547–0.636
Nerodia floridana[c]	0.78	C,P	0.856	0.732–0.829
Thamnophis sauritus[c]	0.77		0.737	0.520–0.650
Nerodia fasciata[c]	0.75		0.793	0.657–0.696
Lampropeltis triangulum[c]	0.73	C,P	0.717	0.519–0.638
Sistrurus miliarius[c]	0.66	C,P	0.722	0.547–0.653
Agkistrodon piscivorus[c]	0.61		0.754	0.631–0.680
Crotalus horridus[c]	0.61	C,P	0.691	0.557–0.612
Cemophora coccinea[c]	0.42	C	0.664	0.517–0.646
Farancia abacura[c]	0.26		0.712	0.619–0.708
Pantherophis gutattus[c]	0.24		0.633	0.554–0.622
Regina septemvittata	0.13		0.544	0.448–0.592
Heterodon platirhinos	0.02		0.584	0.538–0.618
Nerodia sipedon	0.01	C,P	0.507	0.479–0.531
Pituophis melanoleucus	−0.02	C,P	0.634	0.559–0.710
Tantilla coronata	−0.04		0.573	0.491–0.662
Coluber constrictor	−0.07		0.566	0.563–0.597
Storeria occipitomaculata	−0.10		0.558	0.538–0.621
Agkistrodon contortrix[d]	−0.11		0.556	0.562–0.597
Lampropeltis getula	−0.13	C,P	0.552	0.548–0.610
Coluber flagellum	−0.16	C	0.658	0.631–0.733
Virginia striatula	−0.17		0.537	0.504–0.655
Nerodia erythrogaster	−0.18		0.628	0.627–0.688
Diadophis punctatus[d]	−0.24		0.525	0.548–0.611
Thamnophis sirtalis[d]	−0.25		0.526	0.550–0.610
Lampropeltis calligaster[d]	−0.29		0.515	0.532–0.625
Virginia valeriae[d]	−0.34	C	0.504	0.513–0.634
Heterodon simus	−0.36	C,P	0.654	0.641–0.769
Opheodrys aestivus[d]	−0.38	C,P	0.501	0.554–0.606
Pantherophis alleghaniensis[d]	−0.53		0.470	0.564–0.594
Carphophis amoenus[d]	−0.61		0.453	0.555–0.605
Storeria dekayi[d]	−0.98		0.383	0.549–0.613

[a]Positive numbers indicate a species was found in more natural landscapes than expected based on bootstrapped samples and negative numbers indicate a species was found in more human-dominated landscapes than expected based on bootstrapped samples.
[b]Abbreviations: C, species with conservation status of anything other than apparently secure or secure as assigned by NatureServe or anything other than least concern as assigned by International Union for Conservation of Nature; P, protected species listed as endangered or threatened by federal or state statutes or listed as a species of special concern by North Carolina or South Carolina natural resource agencies.
[c]Species significantly associated with natural landscapes.
[d]Species significantly associated with human-dominated landscapes.

Table 5. Conservation and statutory status of turtle species ordered by effect size based on the mean natural landscape value of their occurrences and 95% confidence intervals of means from 1000 bootstrapped samples of all turtles within the species' biogeographic range.

Species	*Effect size*[a]	*Status*[b]	*Mean*	*95% CIs*
Clemmys guttata[c]	0.76	C,P	0.605	0.395–0.502
Malaclemys terrapin[c]	0.59	C,P	0.700	0.523–0.652
Trachemys scripta[c]	0.42		0.545	0.435–0.478
Sternotherus odoratus	0.18		0.525	0.440–0.540
Pseudemys concinna	0.16		0.479	0.407–0.483
Apalone spinifera	0.07	C,P	0.473	0.390–0.543
Kinosternon subrubrum	0.07		0.475	0.425–0.491
Terrapene carolina[d]	−0.13	C	0.439	0.455–0.476
Chelydra serpentina[d]	−0.24		0.416	0.440–0.491
Chrysemys picta[d]	−0.38		0.382	0.431–0.480

[a] *Positive numbers indicate a species was found in more natural landscapes than expected based on bootstrapped samples and negative numbers indicate a species was found in more human-dominated landscapes than expected based on bootstrapped samples.*
[b] *Abbreviations: C, species with conservation status of anything other than apparently secure or secure as assigned by NatureServe or anything other than least concern as assigned by International Union for Conservation of Nature; P, protected species listed as endangered or threatened by federal or state statutes or listed as a species of special concern by North Carolina or South Carolina natural resource agencies.*
[c] *Species significantly associated with natural landscapes.*
[d] *Species significantly associated with human-dominated landscapes.*

cant landscape association. This difference in protection status among the 3 groups was marginally significant ($\chi^2 = 5.6$, df $= 2$, $p = 0.06$).

The 61 rare species with too few occurrences for analysis were disproportionately of conservation concern or legally protected relative to the 91 species with enough occurrences for analysis (85.3% vs. 26.4%; $\chi^2 = 49.9$, df $= 1$, $p < 0.001$). Rare frogs were reported from landscapes with high NL values more than all frog species (observed mean NL 0.706 vs. 95% bootstrapped sample means 0.534–0.633). Rare salamanders were reported from landscapes with high NL values more than all salamander species (observed mean NL 0.644 vs. 95% bootstrapped sample means 0.529–0.596). Rare snakes were reported from landscapes with high NL values more than all snake species (observed mean NL 0.716 vs. 95% bootstrapped sample means 0.621–0.710). Rare turtles were reported from landscapes with high NL values more than all turtle species (observed mean NL 0.627 vs. 95% bootstrapped sample means 0.399–0.528). Even pooled, rare lizard species had fewer than 20 total occurrences and were therefore not analyzed.

Discussion

Predicting how species will respond to changes in land use requires an understanding of their sensitivity to human land uses or dependence on natural landscapes. Such information can identify sensitive species not found in human-dominated landscapes and can allow conservation practitioners to mobilize conservation attention to minimize future declines. It can also help minimize unneeded conservation effort for species that may be more tolerant of, or even benefit from, human-dominated landscapes. Our analyses of 5 major taxa of amphibians and reptiles provide examples of how large data sets of species occurrences generated from citizen science atlases can be used to examine species' sensitivities to human land use.

Atlas data can be problematic due to variation in species detectability, observer experience, sampling effort, and the opportunistic nature of many reported occurrences (Dickinson et al. 2010; Robertson et al. 2010). For instance, people often have an intrinsic fascination with snakes (Isbell 2006); thus, snakes may be overreported in citizen science atlases relative to other reptiles (Price & Dorcas 2011). We accounted for potential variation in detection and the propensity to report some taxa more often by comparing within a taxon the naturalness of landscapes where species occurred because similar species were likely to be found by similar search effort and reported with similar frequency. Our implicit assumption was that species within a taxon have similar likelihoods of being detected and reported. Although rare species may be less likely to be encountered and more likely to be reported when found by some people (Dickinson et al. 2010), the nature of the CHA—with many citizen scientists each reporting a few observations—makes it unlikely such systemic reporting bias would influence our results.

A large source of potential bias in atlas data is variation in sampling effort across habitats, which can lead to mistaken inferences about species' associations with certain habitats (Higa et al. 2015). We addressed this potential bias by comparing the observed mean NL value of each species' occurrences with that of an equal number of occurrences drawn at random 1000 times from all possible reports of all species in its taxon within its range. For example, even if sampling effort in general is far greater near urban and suburban areas, only a species reported from more human-dominated landscapes relative to all others in its taxon would be classified as associated with human-dominated environments. This procedure explicitly controlled for spatial variation in sampling effort and concomitant environmental bias in sampled locations relative to the entire study region. To our knowledge, this approach has not been applied previously to the analysis of citizen science data on species occurrences. However, species distribution models have used occurrences of related species collected through similar survey methods as a sample population against which one can compare the distribution of a focal species (Phillips et al. 2009). Accounting for spatial bias in sampling when conducting species distribution modeling has provided better inferences about the relationship between species occurrences and environmental variables and led to improved model predictions (Phillips et al. 2009; Hertzog et al. 2014).

Our bootstrap procedure produced a comparative assessment of species sensitivities relative to others in its taxon, but it did not provide an absolute measure of a species' sensitivity to land use. Because we included each focal species with all other background occurrences when bootstrapping, our analysis provided a conservative estimate of a species' ranked sensitivity; species with many reports were less likely to differ significantly from bootstrapped samples because the species itself was included among them. Abundant, common species that are highly reported by citizens, however, are expected to be generalists (i.e., capable of persisting across a much broader range of land-cover types than species highly associated with natural or human-dominated landscapes).

In general, the species we identified as significantly associated with natural areas were over twice as likely to be legally protected or warrant conservation concern by state resource agencies than species with no significant landscape associations. They were also over 3 times more likely to be legally protected or warrant conservation concern by state resource agencies than those from significantly human-dominated landscapes. Many of the species associated with natural areas were restricted to land-cover types that have decreased dramatically in the Carolinas. For example, isolated wetlands have disappeared across much of the United States (Dahl 2000). Many species that depend on isolated wetlands were those predicted by our models to be sensitive to human land use, such as the frogs *Hyla femoralis*, *Lithobates sphenocephalus*, and *L. virgatipes*, the salamander *Ambystoma talpoideum*, the snakes *A. piscivorus, Nerodia fasciata*, *Nerodia floridana*, *Seminatrix pygaea*, and *Thamnophis sauritus*, and the turtle *Clemmys guttata*. Other species depend on intact Appalachian forests or the nearly eradicated longleaf pine savannas (Noss 1989). These species too were predicted by our models to be sensitive to human land use, including the frog *Lithobates sylvaticus*, the salamander *Aneides aeneus*, the lizard *Aspidoscelis sexlineata*, and the snakes *Cemophora coccinea*, *Crotalus horridus*, and *Lampropeltis triangulum*. Whereas species we identified as associated with natural areas were more likely to have a higher level of protection than species associated with human-dominated landscapes, 64.3% of species associated with natural areas lacked protection or species of concern designation at the state or federal level. Given these findings, we suggest conservation agencies pay close attention to trends in populations of these 18 species and the 8 species designated only as of special concern by state agencies. Our results suggest these species may rely on natural habitat and are at risk of decline should they lose it.

Our models also identified several species within most taxa that were reported from more human-dominated landscapes. Although it is tempting to treat these species as robust to loss of their natural habitats, our results provide only comparative rankings of which species are less sensitive to human-dominated landscapes than others. Our findings should not be interpreted to mean that any species is completely insensitive to human land use; rather, they mean some species are less sensitive than others in their taxon. For example, our model predicted that the streamside salamanders *Desmognathus quadramaculatus* and *Gyrinophilus porphyriticus* are sensitive to human land use, whereas 2 other streamside salamanders, *Eurycea cirrigera* and *Desmognathus fuscus*, are reported more often from human-dominated landscapes. *Desmognathus quadramaculatus* and *G. porphyriticus* are highly sensitive to sedimentation and watershed development (Keitzer & Goforth 2012; Surasinghe & Baldwin 2015), in contrast to the less sensitive *E. cirrigera* and *D. fuscus* (Barrett & Guyer 2008; Barrett & Price 2014; Surasinghe & Baldwin 2015). Nevertheless, *E. cirrigera* and *D. fuscus* have declined as urbanization and watershed development have increased in North Carolina (Willson & Dorcas 2003; Price et al. 2012).

Some of the species we identified as relatively insensitive to human-dominated landscapes are known to use such areas. For example, the snake *Lampropeltis calligaster* feeds on rodent pests and is more common in early-successional areas (Richardson et al. 2006). The snake *Pantherophis alleghaniensis* feeds on diverse endothermic vertebrates, but because it is an edge predator, it benefits from fragmented landscapes that provide access to birds and their nests (Blouin-Demers & Weatherhead 2001). In a similar fashion, 2 of the turtles reported from human-dominated landscapes, *Chelydra serpentina* and *Chrysemys picta*, benefit from habitat created by people; they are common in farm ponds and golf course ponds and in urban waterways now ubiquitous in much of the eastern United States (Conner et al. 2005; Guzy et al. 2013; Price et al. 2013). All 4 of the aforementioned species were significantly more associated with human-dominated landscapes than were others in their taxa. Our results suggest these species may be able to persist in degraded or converted habitats, but we cannot say definitively that these species are not negatively affected by habitat loss. To confirm that these species are capable of persisting in human-dominated landscapes would require comparing vital rates and changes in abundance of populations inhabiting both natural and human-altered habitats (Todd & Rothermel 2006).

Loss of natural habitats is one of the greatest challenges affecting the future of biodiversity (Sala et al. 2000), and it is among the greatest current causes of imperilment for many amphibians and reptiles (Stuart et al. 2004; Todd et al. 2010). As conservation practitioners address habitat loss to prevent species declines at large scales in a timely manner, the need for equally large and contemporary data sets will continue to grow (Hobern et al. 2014). Citizen science atlas data can play an important role in creating these data sets because they allow timely and inexpensive data collection that far exceeds the abilities of any one researcher. Many species may already be so rare or their distributions so restricted that they will generally be unreported in citizen science efforts. For many of these rare species, such as the frog *Lithobates heckscheri* and the snakes *C. adamanteus* and *Micrurus fulvius*, habitat loss may have already contributed to their declines, present rarity, or local extinctions (Beane 1998; Martin & Means 2000; Akcali & Pfennig 2014). This idea is supported by our finding that rare species as a whole were significantly more likely to be found in natural landscapes and were 3.2 times more likely to be of conservation concern or legally protected than were species with at least 20 occurrences. Our results thus suggest that for many species not presently rare, analyzing citizen science data in a way that controls for spatial sampling biases can identify which species are at greatest risk from loss of natural habitat. As conservation challenges continue to mount, it will be increasingly important to engage citizens in data collection efforts and to find novel ways of addressing potential biases in the data they collect. We propose that random resampling is an effective way to analyze atlas data and can be applied more broadly to studies of other taxa.

Acknowledgments

We thank K. Greene, E.R. Parker, and M. Thomas for providing comments that improved this paper. Programming for the Carolina Herp Atlas was all done by T. Penev and Davidson College ITS. P. Brantley provided technical support. Funding was provided by Davidson College, the North Carolina Wildlife Resources Commission, the South Carolina Department of Natural Resources, and a Riverbanks Conservation Support Fund grant to M.E.D.

Supporting Information

A summary file of species status assessments, range-map sources, and sample sizes for all species found in North Carolina and South Carolina (Appendix S1) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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