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Latitude-enhanced species-area relationships for conservation planning

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Abstract

Context

Changes in biodiversity patterns have prompted efforts aimed at development of tools for conservation planning. Species-area relationships are useful; however these models could be strengthened with the addition of a latitudinal factor.

Objectives

We built latitude-enhanced species-area relationship models to predict species richness for a variety of common taxa in the eastern United States.

Methods

We used data from complete surveys of East Coast parks in the United States to build latitude-enhanced species-area relationship models for amphibians, birds, freshwater fish, mammals, marine fish, plants, and reptiles. We used data from the published literature and United States Fish and Wildlife Refuges to independently test the accuracy of the models. We demonstrated the utility of all modeled taxa within selected East Coast Protected Areas of the United States.

Results

Our models explained 35-91% of the variation in surveyed species richness, with marine fish, freshwater fish and reptile models exhibiting the strongest relationships (pseudo- $R^2=0.91$, 0.66, and 0.70, respectively). The amphibian model was the weakest and had the lowest accuracy but was the model in which latitude had the strongest influence, explaining 8% of the overall variance. During accuracy testing, all taxa exhibited significant agreement between observed and predicted species richness and explained 75-97% of the variation. Our demonstration showed that when comparing two similarly sized US Protected Areas, the parcel 1.25 degree in latitude lower would likely have one more bird species, four more plant species, and an additional amphibian species.

Conclusions

The latitude term added value to the species-area relationship models for most taxa and proved useful in explaining variation in species richness in areas of the East Coast of the United States. Our latitude-adjusted SAR approach is useful for species richness optimization in conservation planning.

Keywords: Model; Negative Binomial Regression; Species Richness; Taxa; Vertebrates

Introduction

Species-area relationships (SAR) (Gleason 1922; Cain 1938; Connor and McCoy 1979; Lomolino 2000) and the latitudinal diversity gradient (LDG) in species richness (Haffer 1969; Rohde 1992; Hillebrand 2004; Gaston 2007; Field et al. 2009) are two of the best developed and most studied relationships in ecology with relevance to both ecological theory and applied conservation planning.

SARs describe the relationship between the area of a habitat and the number of species found within that area. Larger areas tend to contain more species (Rosenzweig 1995; Gotelli 1995) with relative numbers that follow systematic mathematical relationships (Gleason 1922; Cain 1938). SARs have been used to inform biological processes such as disturbance, competition, and division of niche space and have formed the basis of the theory of island biogeography and reserve design (Palmer and White 1994). SARs have also been used to determine optimal sample size and sample number (Hill et al. 1994), the minimum area of a community (Fridley et al. 2006), the number of species in areas larger than those sampled (Palmer 1990), and as a means to estimate the potential species richness of regions or preserves (Kilburn 1966; De Camargo and Currie 2015).

The LDG describes a pattern in which the species richness of most taxa increases toward the equator (Fischer 1960; Pianka 1966; Hillebrand 2004; Drakare et al. 2006; Qian et al. 2007; Rabosky and Huang 2015). There are many possible causes for this latitudinal diversity gradient (Willig et al. 2003; Mittelbach et al. 2007). The productivity and ambient energy hypotheses

generally state that lower latitudes, which receive more energy inputs, can better support more species (Willig et al. 2003). Several evolutionary-based hypotheses relate evolutionary speed with temperature and in turn speciation rates (e.g. Allen et al. 2002; Mittelbach et al. 2007; Kozak and Wiens 2007). Another theory posits that the strength of biotic interactions at lower latitudes might drive faster speciation rates (Schemske 2009). Alternatively, large scale disturbances (e.g. glaciation) at lower latitudes may have led to faster speciation rates or greater persistence of species (Haffer 1969; Mittelbach et al. 2007; Smith et al. 2014).

Given the importance and ubiquity of these two biodiversity relations, there have been several attempts to combine SARs and the LDG (Barbour and Brown 1974; Lyons and Willig 2002; Drakare et al. 2006; Qian et al. 2007; Solymos and Lele 2012). In particular, Solymos and Lele (2012) set a precedent for the inclusion of latitude as a factor in SARs in their meta-analysis through which they created a hierarchical model framework to study pattern, variation and consequences for prediction. However, their study and other similar studies (Lyons and Willig 2002; Qian et al. 2007) were performed at continental or global scales. Potentially more useful would be a model framework that includes latitudinal factors for a variety of common taxa with a focus on regional scale prediction. Such integration is valuable because it tests whether a joint SAR-LDG relationship can hold across finer scales, extending its generality. Moreover, if such statistical relationships can be supported, they will be established at a scale more suitable for conservation planning, especially as it relates to protected area establishment and expansion (Venter et al. 2014), or conversely to, degradation and degazetement (Symes et al. 2016), or even urban planning (Gordon et al. 2009; Fattorini et al. 2018).

Conservation biologists have commonly used traditional SARs for conservation planning efforts such as the design of preserves (Harte and Kinzig 1997), estimation of the number of extinctions expected under habitat loss (Pimm et al. 1991), overall biodiversity assessment (Scott et al. 1993; Chape et al. 2005), and modeling of multi-scale biodiversity patterns and dynamics based on local community sampling (Šizling et al. 2017). Latitude is also an important factor in conservation planning and is especially relevant for countries that extend over a wide region (such as the US or Chile), or for conservation organizations interested in making investments at different latitudes. There is a substantial difference in land protection given latitude; currently, only 5.3% of the global land area between 50° and 60° north latitude is protected, compared to 9.4% of the tropics (UNEP-WCMC 2002). Latitude is also a primary driver of climatic variation at global and continental scales, with corresponding changes in vegetation patterns (Cramer et al. 2001).

As SARs and the LDG started to be combined, conservation biologists used both concepts to inform planning and management. Latitude is a geophysical element that provides a basis for climate-sensitive conservation planning (Anderson and Ferree 2010; Lawler et al. 2015). One such example is the use of a latitudinal factor, as a proxy for climate change, to estimate the number of species of each taxa under current and future conditions, assuming that taxa experience northward shifts in latitude with increasing climate change (Horton et al. 2009; Horton et al. 2015a; Horton et al. 2015b).

In our study, we endeavored to create SARs with a latitudinal factor (which we will heretofore call SAR-lat models) to estimate the number of species for a variety of taxa at the regional scale.

We built our models for amphibians, birds, freshwater fish, mammals, marine fish, plants, and reptiles, tested their accuracy, and demonstrated their use for conservation planning purposes over a variety of areas and latitudes for all modeled taxa within selected United States Protected Areas.

Methods

Our overall analysis involved three steps. First, we built our SAR-lat models based on area and latitude to predict species richness for a variety of taxa. Next, we tested our models for accuracy using an independent dataset. Finally, we applied our models to predict species richness for all taxa in selected United States Protected Areas.

To build our SAR-lat models (step 1), we collected species richness totals by taxa, areas and latitudes for 148 locations east of the Mississippi River along the entire east coast of the United States (Appendix A, Figure 1). Locations were included if data were complete collections within the boundary of a national park, refuge, or watershed for any of the seven taxa of interest (amphibians, birds, freshwater fish, mammals, marine fish, plants, and reptiles). Sites included national parks (Integrated Resource Management Applications (IRMA) 2015), The Nature Conservancy land holdings (E. Creveling, personal communication 2015), North Carolina State Parks (North Carolina Division of Parks 2015), United States Fish and Wildlife Refuges (USFWS 2018), urban open space locations (Kiviat and MacDonald 2004), watershed organizations (Stonybrook-Millstone Watershed Association 2015), and public land holdings (Hutcheson Memorial Forest, personal communication 2015; Huyck Preserve 2015; Stillwater

Township 2015), all of which have various levels of human disturbance. We deliberately targeted species lists for areas that varied in size over several orders of magnitude, including small areas appropriate for urban conservation efforts (Appendix A). The years of collection ranged from 2004-2015 for data from published studies; data from databases often had no year included. Latitudes were obtained from Google Maps for the center of each area, and areas (km²) were obtained using park or refuge boundary shapefiles in GIS or from the source data. For freshwater fish, we calculated water areas (km²) from Gap Analysis land cover data (USGS 2011) and used those values in place of land areas.

Marine fish data were a special case (Appendix B, Figure 1). We obtained data on marine fish species richness for 30 estuaries and bays on the east coast of the United States primarily from NOAA's Estuarine Living Marine Resources program (Jury et al. 1994; Estuarine Living Marine Resources Database 2016). Additional sources are listed in Appendix B. The years of collection ranged from 1978-2016 for data from published studies; data from databases often had no year included. Areas of bays and estuaries were obtained from the National Estuarine Inventory Data Atlas volume 1 (Branch 1985), Statistical Abstract of the United States (United States Bureau of the Census 2000) or from the source data. Latitudes were obtained from Google Maps for the center of each area.

Given that we had counts for species richness, we first considered a Poisson distribution. However, tests for overdispersion of each taxa indicated that a negative binomial distribution would be a better fit going forward. We used R version 3.1.1 to model richness for each taxa with a log-link negative binomial function based on the explanatory factors natural log of land

area (km²) and natural log of latitude (degrees). Based on the LDG we assumed that species richness would decline as the inverse of latitude and felt that it would be informative to estimate the power rather than assuming it to be -1. Thus, we used the natural log of latitude in our model (Barbour and Brown 1974; Adler et al. 2005; Hurlbert and Jetz 2010). Our models allow area and latitude to have different effects on species number but do not include an interaction term (Barbour and Brown 1974; Adler et al. 2005; Hurlbert and Jetz 2010). Comparisons of models with and without a transformation for latitude and with and without an interaction term either performed equally or worse than our log-link model without an interaction term. We used Cox-Snell pseudo R-square as a measure of the goodness of fit of the negative binomial model (Wang et al. 2015). Statistical significance was tested at $\alpha = 0.05$.

We tested the accuracy of our SAR-lat models (step 2) by compiling 145 independent field collected datasets (observed data) from published papers and United States Fish and Wildlife Service refuges (USFWS 2018) to serve as an out-of-sample test of model predictions. Only collections with complete species lists and defined areas were included (Appendix C). The years of collection ranged from 1976-2004. Some collections included latitude values. When latitudes were not available, we used place names in Google Maps to find locations and determined latitudes as the center of each location. We sought to develop a data set that would include a wide variety of areas and latitudes. Thus, areas in the data set ranged from 0.00011 to 4,563 sq km and latitudes ranged from 28 to 56 decimal degrees. Observed and predicted species richness values were compared for each taxa using Pearson correlation and linear regression models constrained to pass through zero in R version 3.1.1. Statistical significance was tested at $\alpha = 0.05$.

We demonstrated the use of our SAR-lat models (step 3) to predict species richness of all modeled taxa within selected United States Protected Areas (PAD-US; USGS 2018). For land-based taxa (amphibians, birds, mammals, plants, and reptiles), we selected from the complete database of nearly 200,000 nationwide sites only east coast locations designated recently as priority areas (since 2012) but with no known mandate for protection and with open access. We applied these restrictions to focus on locations that may benefit the most from our analysis, and to reduce the number of sites to a manageable size for demonstration purposes. To model freshwater fish, we used the marine protected areas dataset from within the United States Protected Areas (USGS 2018) database and selected only east coast locations with < 10% marine area and no site restrictions. Our selection for marine fish was the same but we selected locations with 100% marine area instead. We used the coordinates of the centroid of each polygon to determine its latitude. All three selected sets (land-based taxa, freshwater fish, and marine fish) encompassed a range of areas and latitudes. Generally areas ranged from 0.01-1 sq km for land-based taxa and 0.01-100+ sq km for freshwater and marine fish from Florida/South Carolina to New Hampshire.

Results

Our models followed a typical power function curve with an initial rapid rise in richness from 0 with increasing area, followed by a tendency toward an asymptote. This relationship is depicted with straight lines when the log values of species richness and area are plotted (Figure 2). Our models also exhibit a mostly linear relationship with latitude in which lower latitudes support

more species (Figure 3). Given our model predictions, for a given area, we should expect to find the least richness in the taxa reptiles, with progressively higher richness of mammals, amphibians, marine fish, freshwater fish, birds and plants, respectively.

Our negative binomial models explained 35-91% of the variation in surveyed species richness (Table 1) based on pseudo- R^2 values. The model for marine fish explained the most variation (pseudo- $R^2=0.91$), though reptiles (pseudo- $R^2=0.70$) and freshwater fish (pseudo- $R^2=0.66$) also achieved good model fits. Our weakest model was for amphibians (pseudo- $R^2=0.35$). The remaining models all clustered in the range pseudo- $R^2=0.44-0.49$.

We compared our negative binomial models with a latitude term to those without the term to better understand the explanatory power gained by the inclusion of latitude into the model. On average, across all taxa, the latitude term increased explanatory power by 8.4% (Table 1). The model for reptiles gained the most explanatory power through inclusion of the latitude term (33%) and plants and mammals the least (<1% to 1%, respectively). The rest of the modeled taxa gained from 3-8% through inclusion of the latitude term (Table 1).

We tested accuracy of the SAR-lat models against independently collected data (Appendix C). All the taxa exhibited significant agreement between observed and predicted species richness values, with models explaining 75-97% of the variation (Table 2). Our predictive bird model explained 97% of the variation in observed bird richness, and the observed and predicted values were highly correlated ($r=0.97$, $n=13$). Marine fish, freshwater fish, mammals and reptiles were similarly strong ($R^2=0.90-0.93$) with significant correlations ($r =0.81-0.92$). Our weakest model,

though still significant, was our amphibians model ($R^2=0.75$, $p=0.0001$, $r=0.86$, $n = 14$). Where differences existed, model predictions were generally higher than the observed species richness values.

Slopes and associated standard errors of the regression models in the accuracy study were used to tell if the predictions were of the right magnitude. A value of 1 indicated that the slope does not differ from a 1-1 line which was our goal. The bird, plant and reptile models had slope values very close to 1 (0.99, 1.02 and 1.11, respectively) and low standard errors (0.05, 0.06 and 0.08, respectively) (Table 2). The remaining models had slope values deviating slightly more (0.45–1.77; Table 2).

Our results (Appendix D) from the species richness predictions for land-based taxa in US Protected Areas demonstrated an expected decrease in richness when moving northward along the eastern coast of the United States. Plant richness was predicted to be 24% higher, bird richness 32% higher, amphibian and mammal richness 50% higher, and reptile richness 120% higher in South Carolina at the Oak Brook Nature Trail than at the Hay Barn Lot in New Hampshire for similar size protected areas (0.05 sq km). We see roughly similar predicted species richness values for all land-based taxa at the Oakbrook Nature Trail in South Carolina and the City of Chesapeake Easement in Virginia which indicates that for a ~4 degree increase in latitude, a ~400% increase in area would be needed to retain similar richness. Exchange Park in Georgia stands out as a location with high predicted species richness for all land-based taxa but with no known mandate for protection.

Similar patterns were seen for freshwater fish (Appendix E) and marine fish (Appendix F) predictions. Higher richness was predicted for freshwater fish at lower latitudes with the Florida Keys Wildlife and Environmental Area expected to be 117% higher in richness than the Augustine Wildlife Area in Delaware for a similar sized parcel (10.50 sq km). Likewise, richness was predicted to be 86% higher for marine fish at the Regina Underwater Archaeological Preserve in Florida when compared with the North Hampton State Beach in New Hampshire for a similar sized area (0.01 sq km). We see roughly similar predicted species richness values for freshwater fish at the Hancock County Marsh Coastal Preserve in Louisiana (47 species) and the Dameron Marsh Natural Area Preserve in Virginia (42 species) which indicates that for a ~7 degree increase in latitude, a ~460% increase in area would be needed to retain similar richness for freshwater fish. The same richness (12 marine species) was predicted for the City of Hawkinsville Underwater Archaeological Preserve in Florida and the H.M.C.S. Saint Francis Exempt Site in Rhode Island which involves a nearly 12 degree shift in latitude and a 550% difference in area. The Santee Coastal Reserve in South Carolina stands out for its high predicted freshwater fish richness (102 predicted species) but manageable size and the Southern Glades Wildlife and Environmental Area in Florida stands out for its high predicted marine fish richness (69 predicted species) and similar size (~120 sq km).

Discussion

Our models explained 35-91% of the variation in surveyed species richness, with marine fish, freshwater fish and reptile models exhibiting the strongest relationships. In general, our results compared favorably to the results from other SAR studies. For instance, Oberdorff et al. (2001)

cited a pseudo- R^2 of 0.77 for freshwater fish; Ormond and Roberts (1997) cited an $R^2=0.72$ for marine fish; King et al. (1997) cited an $R^2=0.49$ for frogs and toads and $R^2=0.66$ for snakes; Case (1975) cited an $R^2=0.53$ for lizards; Kaufman and Willig (1998) cited R^2 values from 0.45-0.50 for mammals; Riebesell (1982) cited an $R^2=0.47$ for plants; and Rahbek (1997) cited an $R^2= 0.48$ for birds in low elevation neotropical countries except Chile and Brazil. Though these comparisons are informative and they underscore the strength of our models, care must be taken in making direct comparisons of R^2 values across multiple studies because they may be based on different bivariate transformations (Lomolino 2001).

Our strongest model was for marine fish (pseudo- $R^2=0.91$); freshwater fish also demonstrated a fairly good fit (pseudo- $R^2=0.66$). The strength of these water-based models compared with the land-based models may derive from the fact that these models used water area instead of land area in their calculations. Water area covered a larger range of areas possibly making these aquatic models more able to account for variation. Our weakest model was for amphibians ($R^2=0.35$) which explained much less of the variability than the rest of the models but in which latitude had the strongest influence (explaining 8% of the variance). Amphibians heavily utilize wetland areas for many portions of their life cycle, yet research has noted that there is no relationship between wetland area and amphibian species richness (Snodgrass et al. 2000), underscoring the weak relationship we found in our study.

During accuracy testing, we found that our observed values explained a lot of the variability in our predicted values ($R^2=0.75-0.97$) and demonstrated significant correspondence ($r = 0.81-0.97$). Models for almost all of the taxa exhibited appropriate magnitudes of predictions (as

determined by slopes given in Table 2). The models for freshwater and marine fish deviated the most from a 1-1 line. It is somewhat difficult to find studies that noted both area and complete species lists for aquatic regions. This stems from the fact that aquatic regions often have open boundaries, particularly riverine systems and marine areas. The out-of-sample studies we used may not have been representative and certainly did not include the wide range of areas and latitudes used in creation of the aquatic models. Further research and the availability of more robust out-of-sample datasets would prove insightful.

Given our model predictions, we should expect to find the fewest species of reptiles and progressively more species of mammals, amphibians, marine fish, freshwater fish, birds and plants, respectively, in a location for a given area and latitude. This pattern derives explicitly from the abundances of species for each taxa in the data we used to create the models (Appendix A). Though our models were built across a range of spatial scales and included a variety of heterogeneous landscapes, caution may be required in interpreting results as they do not thoroughly account for such landscape features as topographical heterogeneity (elevational changes), human induced changes such as habitat fragmentation (Lomolino 2001), habitat shape/connectivity, and ecosystem conversion.

All of our negative binomial models followed a power function between species richness and area and an inverse relationship between species richness and latitude, both of which have been observed previously in the literature (Gleason 1922; Hillebrand 2004). The power function enables richness to go to zero with decreasing area. The inverse relationship between species richness and latitude, as shown by the negative latitude coefficients for all taxa, is responsible for

richness increasing toward the equator and away from the poles, as is commonly observed (Barbour and Brown 1974; Hillebrand 2004).

The power function relationship produces straight lines when the log values of species richness and area are plotted. The slopes of the lines are related to rates of species turnover (Rosenzweig 1995; Arita and Rodríguez 2002) and this relationship holds across a range of areas and scales (Šizling et al. 2017). Greater slopes correspond to faster accumulation of species as area increases indicating higher rates of species turnover (Arita and Rodríguez 2002). In our models, mammals had the steepest slope (0.23), followed by plants and marine fish (0.20 and 0.19), respectively. Thus, these taxa are likely to experience higher rates of species turnover with increasing area.

The issue of scale is important in our study. For some taxa, our models span spatial scales that would represent habitat selection, for others metapopulation scales. Our models were thus designed to be used at the regional scale unlike other similar studies that have focused at continental or global scales (Lyons and Willig 2002; Qian et al. 2007; Solymos and Lele 2012).

Our study was not designed to test which of the many hypotheses regarding the LDG (see extensive review by Willig et al. 2003) are applicable for our sample from the eastern United States, yet we do see a strong latitudinal effect. Our demonstration showed that when comparing two similarly sized Protected Areas, the parcel 1.25 degrees lower in latitude would likely have one more bird species, four more plant species, and an additional amphibian species. We also found that latitude explained more of the variation for amphibians (8%) than for birds (5%) or

mammals (1%). If such results are explained by differences in ambient energy (e.g. potential or actual evapotranspiration) as suggested by some (e.g. Pianka 1966; Currie 1991), then one might think of latitude as a very simple surrogate for climate change effects on species richness.

We can utilize results from our SAR-lat models in a variety of different ways but looking at the pattern in a vacuum can be misleading. We will almost surely find more species towards the tropics, but areas more to the north are no less relevant for conservation. The field of conservation has recognized a need to manage whole landscapes that fulfill two roles: a) to represent the biodiversity of each region, and b) to separate this biodiversity from processes that threaten its persistence (Margules and Pressey 2000). Choosing regions to conserve based only on patterns driven by latitude may fulfill the first role but not the second. Thus, while areas at more northern latitudes may have lower species richness, the species will likely be different, and the areas likely have a range of ecological functions, ecosystem services, and threats which differ from those at lower latitudes. A more systematic approach to conservation planning has been evolving (Margules and Pressey 2000) and this approach must be considered when choosing locations for conservation.

With all of this in mind, we demonstrated the utility of our models for conservation planning purposes at multiple scales and latitudes by predicting species richness for all modeled taxa within selected United States Protected Areas. A conservation scientist might ask the question: looking regionally, which of our recently acquired holdings have no current plan for protection but support high richness for multiple land-based taxa? This question is even more relevant when faced with the fact that limited funding often exists to maintain diversity and that many

organizations have land holdings or invest in conservation efforts spread across an area covering many degrees of latitude (e.g. Audubon, The Nature Conservancy, etc). Our models answered this question by showing that resources might be well spent by focusing on a location such as Exchange Park in Georgia which has no current plan for protection and, in part due to its lower latitude, supports high richness for all land-based taxa despite being similar in size to other areas in the list. Similarly, we were able to discern locations where resources might be best spent for freshwater and marine fish species richness protection. This process provides a starting point in terms of planning given caution is taken to consider all aspects of a systematic conservation approach in the process of decision making (Margules and Pressey 2000).

A conservation scientist might next ask a different question that we can also answer: how much of a difference does latitude make in similar sized protected areas at the regional scale? Within New Hampshire, for instance, a 0.6 degree decrease in latitude would likely result in one more bird species and four more plant species. Latitude has not historically been appreciated with regard to protection of areas at the regional scale (e.g. nowhere is the term mentioned in the seminal papers by Scott et al. 1993; Myers et al. 2000; Yoccoz et al. 2001). With information from our models, a conservation scientist might create a starting point for discussion of areas to consider for additional resources and support.

It is clear that the latitude term added value to the species-area relationship models for most common taxa and proved useful in explaining variation in species richness across the eastern United States. Actual species diversity will depend on a wide set of additional factors, including the regional species pool, ecosystem composition, and human management. However, the

statistical models explored here move forward the process of developing methods to optimize species richness in conservation planning.

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Table 1: Models were built using negative binomial regression to predict species richness for multiple taxa on the east coast of the United States. Parameters are given for model fit (number of observations (N), pseudo-R², Z values and P values), coefficients, and explanatory power of the latitude term. The equation of the models is of the form $\exp(a+b*\ln(A)+c*\ln(L))$ where $\ln(A)$ is the natural log of area, $\ln(L)$ is the natural log of latitude, and a, b, and c are model coefficients. For freshwater and marine fish, water area was used for area instead of land area. The explanatory power of the latitude term was determined through comparison of the models with and without the latitude factor. All coefficients are significant at the $p < 0.0001$ significance level. Remaining factors are significant at the $p < 0.05$ level.

Taxa	N	pseudo-R ²	Z value Area	P value Area	Z value Latitude	P value Latitude	Coefficient a	Coefficient b	Coefficient c	Explanatory power of latitude term (%)
Amphibians	130	0.35	6.829	<0.0001	-3.404	<0.0001	7.734	0.132	-1.464	0.08
Birds	128	0.44	7.547	<0.0001	-2.816	0.005	8.552	0.139	-1.063	0.05
Fish (freshwater)	72	0.66	7.315	<0.0001	-2.777	0.006	9.680	0.151	-1.644	0.08
Fish (marine)	30	0.91	6.650	<0.0001	-2.353	0.019	6.854	0.185	-1.084	0.04
Mammals	129	0.49	9.435	<0.0001	-2.118	0.034	6.924	0.227	-1.166	0.01
Plants	108	0.45	7.182	<0.0001	-1.974	0.048	11.182	0.199	-1.485	0.00
Reptiles	129	0.70	8.103	<0.0001	-8.792	<0.0001	14.063	0.153	-3.196	0.33

Table 2: Results of correlation and regression analysis to compare observed and predicted species richness. Regression analysis was constrained to pass through 0. Results of correlation and regression are all significant at the $p < 0.05$ level.

Taxa	N	Correlation	Adj- R ²	Slope	Slope standard error	F- value	<i>P</i>
Amphibians	14	0.86	0.75	1.36	0.21	42.67	<0.0001
Birds	13	0.97	0.97	1.00	0.05	445.3	<0.0001
Fish (freshwater)	15	0.81	0.91	1.77	0.15	146.5	<0.0001
Fish (marine)	13	0.81	0.93	0.45	0.03	186.7	<0.0001
Mammals	15	0.89	0.90	1.32	0.11	133.7	<0.0001
Plants	57	0.96	0.85	1.02	0.06	328.7	<0.0001
Reptiles	19	0.92	0.90	1.11	0.08	178.1	<0.0001

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Figure 1: Locations of data collections used in formulation of species-area and latitude relationships. White triangles represent 30 locations with marine fish species richness values; black dots represent 148 locations with species richness values for all taxa except marine fish.

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Figure 3: Species-latitude relationships for latitudes of 32.05, 35.23 and 40.71 degrees N for amphibians, birds, freshwater fish, mammals, marine fish, reptiles, and plants given an area of 1 sq km.

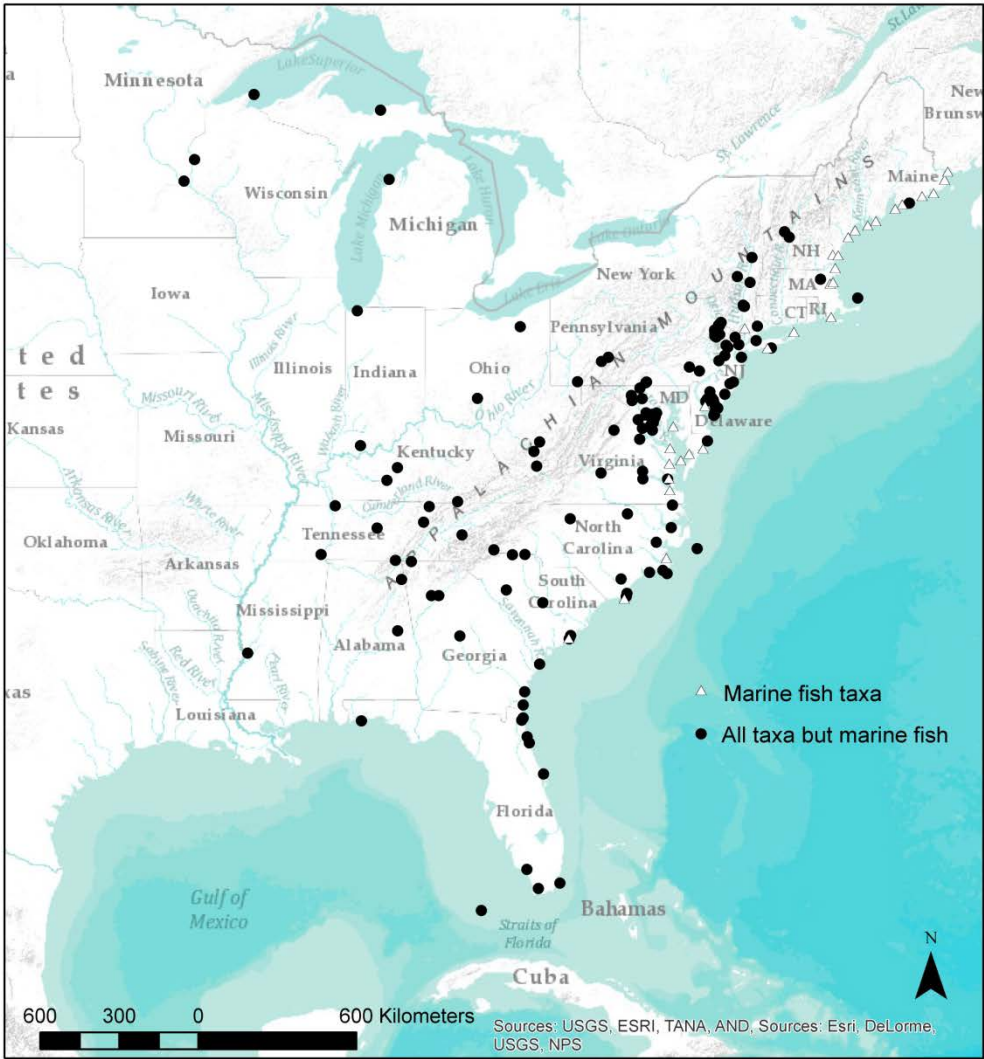


Figure 1.

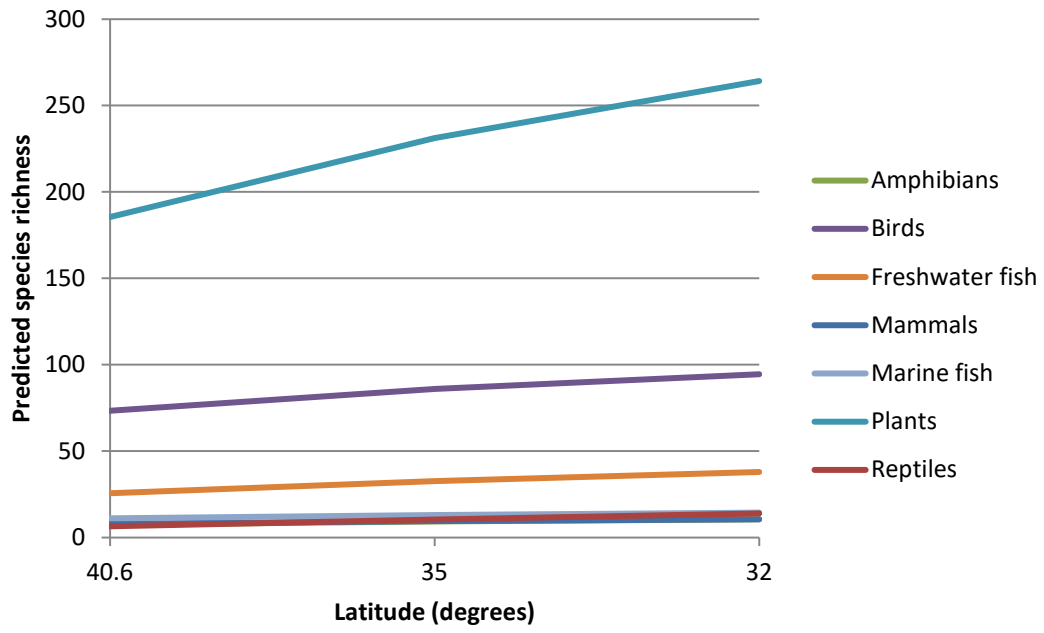


Figure 2.

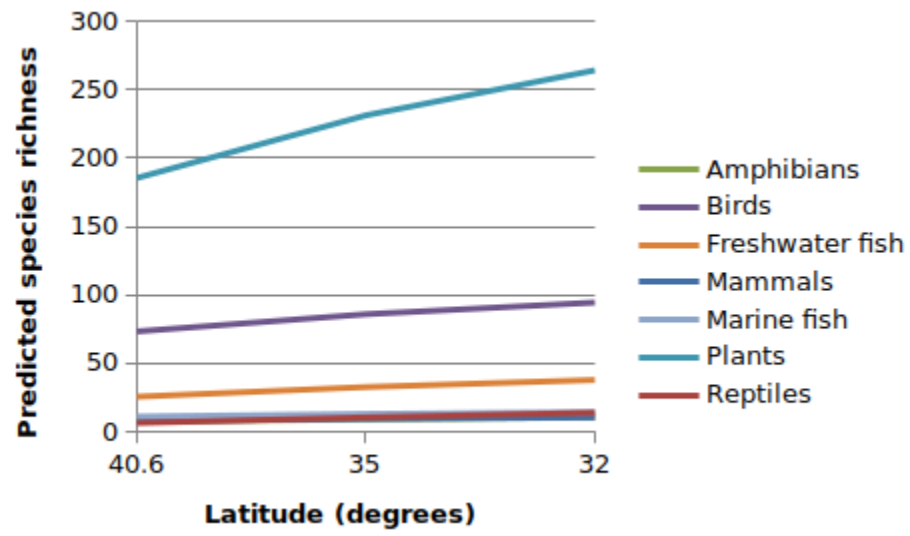


Figure 3.

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Appendix A: Species richness data used for latitude-enhanced species-area curve formulation for amphibians, birds, freshwater fish, mammals, plants and reptiles. Sources reference species richness values. Land areas were obtained using park or refuge boundary shapefiles in GIS or from the source data for richness values. For freshwater fish, we calculated water areas from Gap Analysis land cover data (USGS 2011) and used those values in place of land areas. Latitudes were obtained from Google Maps for the center of each area.

Appendix B: Species richness data used for latitude-enhanced species-area curve formulation for marine fish. Sources reference species richness values. Areas of bays and estuaries were obtained from the National Estuarine Inventory Data Atlas volume 1 (Branch 1985), Statistical Abstract of the United States (United States Bureau of the Census 2000), or from the source data for richness values. Latitudes were obtained from Google Maps for the center of each area.

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Appendix E. Predicted species richness for freshwater fish at multiple scales and latitudes: demonstration of models for conservation planning purposes. Source data from the United States Protected Areas Database (PAD-US) (USGS 2018).

Appendix F. Predicted species richness for marine fish at multiple scales and latitudes: demonstration of models for conservation planning purposes. Source data from the United States Protected Areas Database (PAD-US) (USGS 2018).