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EVALUATING THE VULNERABILITY OF WYOMING'S WILDLIFE TO HABITAT DISTURBANCE

By
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All data and models referenced herein are available from the Wyoming Natural Diversity Database (http://www.uwyo.edu/wyndd/index.html); requests should reference the Assessment of Wildlife Vulnerability to Energy Development project.

TABLE OF CONTENTS

INTRODUCTION

There has recently been much debate over the validity, causes and potential impacts of an impending ‘biodiversity crisis’ stemming from rapidly increasing rates of extinction that likely result from anthropogenic disturbances to formerly intact landscapes (Koh et al. 2004, Wake and Vredenburg 2008). Continuation of these trends will result in natural resource managers being faced with conservation decisions relative to a large and growing number of species in the midst of rapidly changing landscapes. With limited conservation resources, it is necessary to apply strategic planning to prioritize conservation efforts (Margules and Pressey 2000).

The idea that some species are more sensitive to disturbance, and ultimately extinction, than others is not new. However, it was not until the emergence of modern population biology and, moreover, island biogeography theory (MacArthur 1967) and the growing ‘extinction crisis’ of late 20th century that scientists began in earnest to evaluate the forces that cause certain species to be more prone to extinction that others (McKinney 1997). Since the 1970’s, such research has generated many studies examining extinction proneness, and a variety of synthetic treatments (e.g., McKinney 1997, Purvis et al. 2000, Henle et al. 2004). Most recent interest in such inquiry has been driven by conservation concerns, in hopes that the resulting insight would be useful in understanding, and thus mitigating, impacts from human disturbance, or even predicting future impacts that would allow proactive management. Despite these efforts, we still lack a unifying framework in which such information can be fruitfully applied, with the exception of small, related groups of target species under specific circumstances. Two reasons for this lack of generality are the narrow focus of most studies (e.g., restricted geographic scope or narrow taxonomic breadth of the investigation) and the often confusing, interacting nature of factors affecting extinction proneness (e.g., subtle interactions between body size and foraging strategy when examining insectivorous forest birds) (Purvis et al. 2000).

Vulnerability is the state of being susceptible to harm and, at its core, is primarily a function of exposure and sensitivity (Turner et al. 2003, Williams et al. 2008, Pacifici et al. 2015). In order for a species to be vulnerable to disturbance it must both be exposed to the disturbance and it must be sensitive to the disturbance (Fig. 1). Therefore, to accurately assess whether species are vulnerable to disturbance one must first determine whether their preferred habitats coincide with the disturbance (i.e., quantitatively evaluate exposure), and then combine the exposure assessment with an evaluation of the species sensitivity to the particular changes wrought by that type of disturbance (i.e., quantitatively evaluate sensitivity). Few previous studies have carefully assessed both factors in the same system. The advent of desktop Geographic Information Systems has increased the ability to conduct spatially explicit exposure assessments by facilitating geospatial analyses of human impacts, often through 'footprint analysis' (e.g., Leu et al. 2008, Walston et al. 2009), though such studies are limited to coarse scale overlays that do not explicitly evaluate biological sensitivities for the species in question. In contrast, studies evaluating the biological correlates of extinction proneness have generally not been spatially explicit; either evaluating taxon-wide sensitivities with no spatial reference or focusing explicitly on entire target populations.

I assessed the relative vulnerability of Wyoming's terrestrial vertebrate Species of Greatest Conservation Need (SGCN) to disturbance and/or ultimate extinction due to energy development activities. Although the focal landscape for this effort is Wyoming the methods are transferable to other systems. To accurately access vulnerability, I quantified its constituent parts, namely exposure, which is a function of species distributions relative to development, and sensitivity, which is largely a function of species biology (Fig. 1). Chapter 1 explains the development of species distribution models, and Chapter 2 combines those models with spatial estimates of energy development to quantify exposure for all SGCN (*N* = 156). Chapter 3 uses a meta-analysis of habitat fragmentation studies to identify and quantify predictors of sensitivity to local disturbance. Chapter 4 is a brief conclusion that combines estimates of exposure and sensitivity to rank Wyoming's SGCN according to their vulnerability to energy development.

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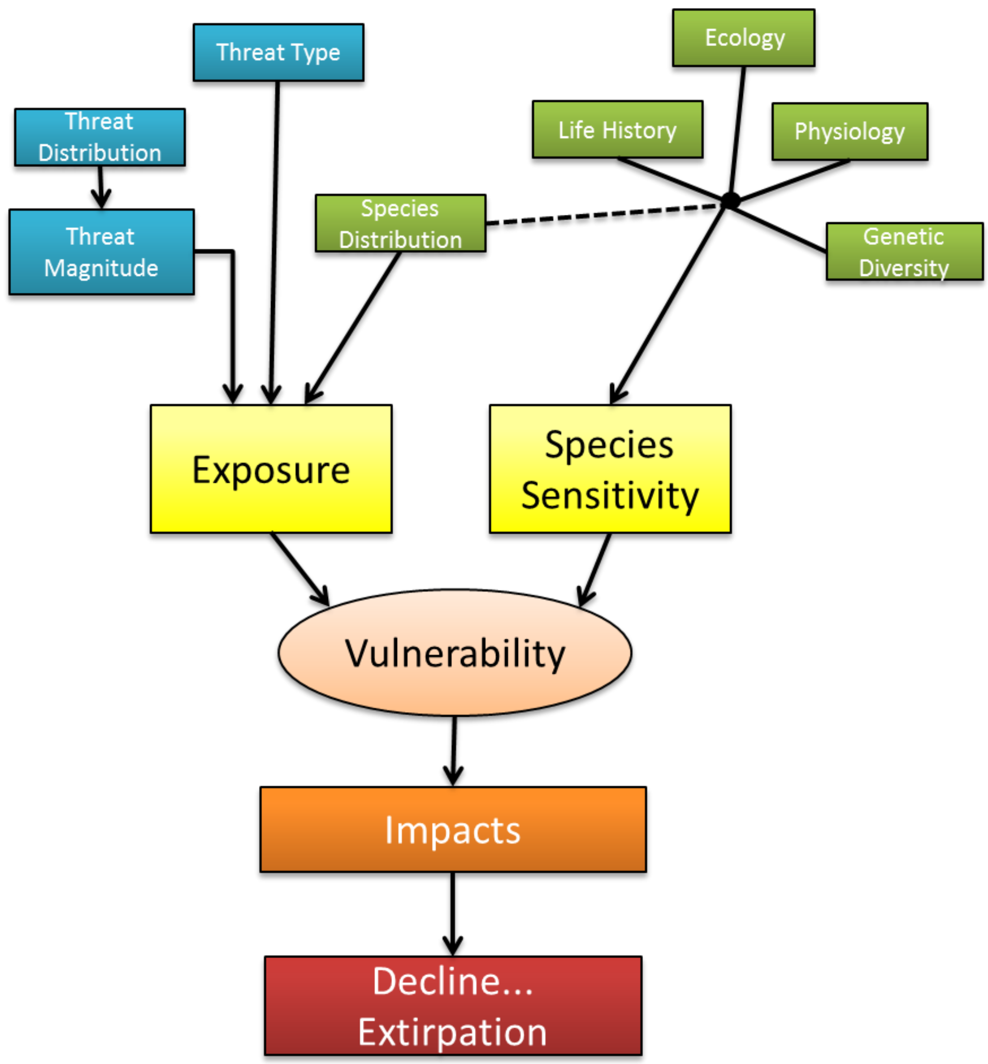
Figures

Figure 1. Schematic diagram relating factors causing disturbance to the decline and endangerment of species. Factors contributing to exposure are largely external drivers (blue), while those contributing to species sensitivity are largely intrinsic to the species in question (green). Exposure and sensitivity interact to determine species vulnerability to a given threat. Loosely adapted from Williams et al. (2008).



CHAPTER ONE

Mapping the distribution of Wyoming's Species of Greatest Conservation Need

***Abstract*: .**Wyoming has many species of conservation need, the distribution and actual status of which are poorly understood. In the face of impending development, there is a need to better define the distribution of these species to assess the potential of their populations to be adversely affected by habitat conversion. Herein, I develop distribution models for 156 of Wyoming's terrestrial vertebrate species of conservation need using a compilation of occurrence records and statewide habitat data. Models were generated using a maximum entropy approach and evaluated using multiple metrics from which I generated an omnibus model quality index. Game species and species receiving attention under the U. S. Endangered Species Act had more and higher quality occurrence data, and consequently distribution models with higher model quality. Small mammals and reptiles had particularly small sample sizes and had lower-quality models. Although low-quality should be used with caution, they can still fruitfully inform conservation efforts by identifying information gaps and serving as hypotheses for more targeted distribution mapping efforts.

Key words: energy development, niche model, SGCN, species distribution model , wildlife, Wyoming

Introduction

There are well over 500 vertebrate animals that naturally occur in the state of Wyoming (Baxter and Stone 1980, Clark and Stromberg 1987, Baxter et al. 1995, Dorn and Dorn 1999). Roughly 200 terrestrial vertebrates have been identified by conservation and management entities as being of potential concern (BLM 2002, Keinath et al. 2003, USFS 2005, WGFD

2010), encompassing a range of species with different life histories and habitat needs. Of these species, nine have been formally listed under the federal Endangered Species Act, 19 more have experienced some listing efforts over the past few decades, and others could be petitioned for listing if their status declines. In their State Wildlife Action Plan (SWAP), the Wyoming Game and Fish Department (WGFD) identified 152 terrestrial vertebrate Species of Greatest Conservation Need (SGCN), many of which were included as a precaution due to a lack of information regarding their distribution and conservation status (WGFD 2005, 2010). For 80% of SGCN, more than half of their range in Wyoming is assumed in the absence of actual observations (Fig. 1). In the coming years, habitat alteration is expected to drastically increase throughout Wyoming, and while detailed distributional information is lacking, large portions of habitat for many SGCN are suspected to fall in areas currently under development and/or planned for future development. Therefore, a major conservation goal of state wildlife managers is to compile updated information on the range and distribution of SGCN within Wyoming (WGFD 2010).

Methods

The environmental characteristics of locations where species have been documented to occur were used to create species distribution models (SDMs) that predicted areas throughout Wyoming that are potentially suitable for occupation (e.g., Elith et al. 2006, Greaves et al. 2006, Phillips et al. 2006, Guisan and Thuiller 2007). The basic components of SDMs are: 1) occurrence data collection and processing, 2) environmental data collection and processing, 3) model generation, and 4) model validation.

Occurrence Data. We compiled occurrence records (i.e., mapped observations of species at specific locations) for all Wyoming's terrestrial vertebrate SGCN (WGFD 2005) and several additional species currently under consideration as additions to the SGCN list, resulting in a dataset of approximately 270,000 individual records for 156 species. Records were compiled between 2007 and 2010 from a variety of sources. Major sources included the Biotics database of the Wyoming Natural Diversity Database (http://uwadmnweb.uwyo.edu/wyndd/), the Wildlife Observation System (WOS) of the WGFD (see WGFD 2005), data from annual bird monitoring efforts (notably the North American Breeding Bird Survey and surveys for the Monitoring Wyoming's Birds project), specimens from museums across the country (notably the National Museum of Natural History, University of Kansas Natural History Museum, and the University of Michigan Museum of Zoology), and unpublished datasets from local biologists.

At a minimum, records were attributed with their source, collection date, species identification, and geographic location. Where additional information was available (e.g., observer notes), this information was also retained. Positional accuracy (i.e., how closely the observation site could be relocated from information in the record) was estimated based on the record's mapping protocol using standards established by the Natural Heritage Network (http://www.natureserve.org/prodServices/standardsMethods.jsp). All records were stored in a geodatabase that was queried as needed for analysis and modeling.

Sources varied in terms of data structure, positional accuracy, dates of collection, veracity of species identification, and the detail of supporting biological data provided, necessitating efforts to reconcile differences to form a single, logically-consistent dataset. Moreover, individual observations varied greatly in their quality, and were not of equal value for constructing distribution models. We scored each record for three key criteria: date of observation; precision of reported observation location; and veracity of species identification (Table 1), and added these scores to compute a point quality index (PQI) for each record. Thus, high-quality points (i.e., those that were recent, accurately located, and positively identified) could achieve a maximum score of 12, while poor-quality points received a minimum score of 0. These scores were used to filter data prior to niche modeling and to assess the overall quality of the available data for each model. We removed all unusable points from the dataset (i.e., points that had a score of 'U' for any quality measure; Table 1).

For most migratory species, the primary season of interest in Wyoming was the breeding season, because these species migrate outside the state during the non-breeding season. In these cases, all non-breeding season occurrences were eliminated. Well-documented occurrences often specifically noted evidence of breeding, but where this was not the case estimates of breeding/migratory phenology from published species accounts (notably Birds of North America accounts; http://bna.birds.cornell.edu/bna/) were used in combination with local knowledge to estimate the timing and duration of the breeding season. For migratory species, all occurrences outside the designated modeling season were removed from the dataset.

Opportunistically-collected datasets can suffer from autocorrelation artifacts arising from non-uniform sampling across the area of interest, which can sometimes bias environmental niche models (Jimenez-Valverde and Lobo 2006, Johnson and Gillingham 2008). To mitigate this problem, we thinned dense clusters of occurrences resulting from oversampling by removing those occurrences with lower PQI scores that were within 1,600 meters (roughly one mile) of other, higher-quality occurrences. Where equal quality occurrences occurred within 1,600 meters, we randomly selected which occurrence to remove. We then constructed model sets by randomly drawing occurrences with geographic stratification based on 12-digit hydrologic units. This was accomplished by first selecting the best quality (i.e., highest PQI) point from each occupied hydrologic unit. We then added the next-highest quality occurrence from each hydrologic unit to our selection and repeated this until additional occurrences were selected from less than 20% of the previously selected hydrologic units. This cutoff guarded against model bias by preventing occurrences from clustering in a small subset of the species' range. In other words, it helped ensure an even distribution of occurrences across the modeled area, even when sampling was not evenly distributed.

Environmental Data. Environmental data used in modeling was drawn from a set of 73 variables falling within five categories: climate, hydrology, land cover, substrate and terrain (Appendix A). In addition, some species-specific variables (e.g., distance to permanent snowfields, distance to cliffs) were used as appropriate. Detailed information regarding all variables is available online (Keinath et al. 2010).

Climate variables were generated by applying the BIOCLIM algorithms (Nix 1986) to DAYMET climate data (Thornton et al. 1997, Thornton and Running 1999, Thornton et al. 2000). This was done by running ARC/INFO AMLs, written by Robert Hijmans (available at http://worldclim.org) on 18-year DAYMET averages (available at http://www.daymet.org/climateSummary.jsp). Hydrology layers were derived from the National Hydrography Dataset (Simley and Carswell 2009), and comprised metrics representing proximity to water features (e.g., lakes, reservoirs, streams) and degrees of permanence (i.e., ephemeral, intermittent, or perennial).

General land cover variables used in modeling included forest, shrub, herbaceous, and bare ground cover data from the LANDFIRE dataset (Rollins and Frame 2006). Many of the specific vegetation indices that influence individual species' distributions (e.g., percent conifer forest cover, percent deciduous forest cover) were not available in any one dataset, requiring the production of synthetic variables that typically incorporated values from LANDFIRE data

(Rollins and Frame 2006), GAP Land Cover (Comer et al. 2003, National Gap Analysis Program 2010), and/or the USGS Sagebrush dataset (Homer et al. 2012). We created these synthetic indices by first assigning each GAP ecological system a score relative to the desired feature (e.g., dominance of conifer trees in each ecological system) and combining that score with the LANDFIRE estimate of canopy cover to come up with an index for each category that ranged from 0 (e.g., low canopy cover in a system that has a very small conifer component) to 1 (complete canopy cover in an ecological system dominated by conifers). Landscape pattern of land cover was assessed by computing contagion using Fragstats (O'Neill et al. 1988, Turner 1989, Li and Reynolds 1993, McGarigal and Marks 1994) based on a 4-category landscape classification (barren/developed, herbaceous, shrub-dominated, tree-dominated).

Common substrate variables (e.g., soil texture, depth to shallowest restrictive layer) were derived from STATSGO data as expressed in the Natural Resource Conservation Service's Soil Data Viewer 5.1 (Natural Resource Conservation Service 2006). Terrain variables (e.g., elevation, slope, ruggedness) were derived from the National Elevation Dataset (Gesch et al. 2009) using previously published algorithms (Beers et al. 1966, Gessler et al. 1995, Jenness 2006, Sappington et al. 2007).

Model Generation. We created SDMs using documented occurrences of Wyoming's SGCN as the response variable and statewide environmental layers as predictor variables. Models were generated using a maximum entropy approach, as it has consistently shown to be among the most accurate and robust algorithms for constructing distribution models from opportunistically collected data, particularly when sample sizes are small and processes driving distribution are complex (Graham and Elith 2005, Elith et al. 2006, Hernandez et al. 2006, Hijmans and Graham 2006, Phillips and Dudik 2008, Wisz et al. 2008). We used Maxent®

(Phillips 2009) to implement the maximum entropy algorithm and ArcGIS® (ESRI 2011) to spatially project distribution maps onto the Wyoming landscape. For each species, a set of 5-7 predictor variables was selected to construct the distribution model based on knowledge of the species biology and evaluation of variable importance measures from exploratory models.

To further avoid biases associated with opportunistically gathered data (Jimenez-Valverde and Lobo 2006, Graham et al. 2008, Johnson and Gillingham 2008, Veloz 2009), we drew background data from the entire sample set rather than randomly-generated pseudo-absences for model building (Phillips et al. 2009). We created distribution models for all species with final model sets of 5 or more documented occurrence locations, since MaxEnt® has been shown to generate reasonable distribution models with occurrence sets of this size (Hernandez et al. 2006), though these models were penalized when assessing model quality (see Model Validation) to acknowledge the possibility that sampling biases are likely with such low sample sizes.

It should be noted that there has been a recent criticism pointing out that modelers have over-reached in their interpretation when using algorithms like Maxent®, and that other estimators are preferable when assumptions of detection probability are constant, sampling of space is truly random and ecological inference is a primary goal (Royle et al. 2012). This concern does not apply to this study, as our cross-taxonomic data are opportunistic in nature, we are primarily interested in spatial accuracy of prediction rather than ecological interpretation, and our application does not interpret results as truly probabilistic in nature. Further, our use of the Boyce index (Boyce et al. 2002) to evaluate model quality implicitly tests model output relative to the key characteristic underlying this criticism; namely it insures that higher model values are indeed indicative of greater likelihood of species presence. Under the real-world situations of this study, Maxent® has repeatedly been shown to produce robust predictions that are useful when applied with appropriate attention to caveats, as we have done here.

Model Validation. There are a plethora of validation techniques for SDMs, each of which has strengths and weaknesses that must be considered with respect to the goals of the modeling effort (Fielding and Bell 1997), and to achieve robust assessments of model quality, it is often good to employ multiple methods (Franklin 2009). Since predictive accuracy was our primary concern, we used three quantitative metrics designed to evaluate how well models predicted independent test data. First, we calculated area under the receiver operating characteristic curve (ROC AUC; Hanley and McNeil 1982, Bradley 1997, Liu et al. 2005), which is a threshold-independent metric assessing where models perform better than chance. Second, we calculated overall predictive success (i.e., the proportion of occurrences accurately predicted as present) based on a binary representation of the model. Third, we calculated the Boyce index (Boyce et al. 2002, Hirzel et al. 2006, Petitpierre et al. 2012), which measures how model predictions differ from random across the prediction gradient and is thus particularly useful for presence-only data. We used cross-validation to assess the range of variability in these metrics, wherein we built several separate models based on random subsets without replacement, or folds, of the occurrence data. We generally used 10-fold cross-validation (withholding 10% of the occurrence data as a 'test' dataset and using the remaining 90% as a 'training' dataset) to build a distribution model. Species with less than 10 occurrence points were evaluated with fewer folds. We calculated the suite of quantitative evaluation metrics for each of the cross-validation models and summarized the resulting statistics across folds. In addition to the suite of quantitative metrics, we assessed the size and quality of the input dataset and obtained qualitative expert review of the final models.

Despite the logic of using multiple model validation techniques, there is little guidance on how to synthesize information across such metrics. On the whole, models that validate well using multiple metrics are more robust (Franklin 2009, Carvalho et al. 2011). We therefore calculated a model quality index (MQI) that placed several well-supported validation statistics on a 0 to 1 scale and combined them using a simple weighted average (Equation 1).

$$\mathrm{MQI} = \frac{\left(\frac{NOS+OQS}{2}\right)*0.75+\left(\frac{AUC+OES+ERS+BI}{4}\right)}{1.75} \qquad \text{Equation 1}$$

NOS (Number of Occurrences Score): More occurrences, or a larger sample size, lead to more robust models. NOS values of 1 reflect species with more than 100 occurrences; values of 0.75 reflect species with between 50 and 100 occurrences; values of 0.5 reflect species with between 20 and 50 occurrences; and values of 0 reflect species with less than 20 occurrences.

OQS (Occurrence Quality Score): All occurrences were scored based on their quality, as noted in the text and Table 1. These data were used to calculate average occurrence quality for the each model set. The resulting values were rescaled to range from 0 (very poor quality dataset) to 1 (very high quality dataset).

AUC (Area Under the Curve): We calculated the ROC AUC for each cross validation model based on a holdout dataset (Bradley 1997, Fielding and Bell 1997). A value of 0.5 indicates model performance no better than chance, values below 0.5 indicate counter prediction, and values above 0.5 indicate increasingly strong classification to an upper limit of 1.

OES (Omission Error Score): Omission error is the proportion of test data miss-classified using the optimal binary threshold for each cross validation model, where higher values indicate lower quality models. OES was calculated by subtracting the omission error from one.

ERS (Expert Review Score): We scored the final model for each species using a simple categorical system reflecting how well local biologists felt it represented the species' true distribution in Wyoming. "High Quality" models were deemed to represent the species distribution well (ERS = 1). "Medium Quality" models represented the species distribution fairly well, but with minor errors of omission or commission (ERS = 0.5). "Low Quality" models were deemed to be either questionable or beyond our ability to accurately assess (ERS = 0).

BI (Boyce Index): The Boyce index is essentially a spearman rank correlation coefficient (rs) that varies between -1 (counter prediction) and 1 (positive prediction), with values statistically close to zero indicating that the model does not differ from a random model (Boyce et al. 2002). Values closer to 0 indicate poorer model fit. No model in this study had a negative Boyce Index.

When exploring the effect of sample size and occurrence quality on models, we calculated the model quality index omitting the first two components (NOS and OQS). Otherwise, these two components were given slightly less weight than the others, because they are indirect measures of model quality. A model constructed using a small or low-quality sample is likely to be more uncertain, but is not definitively poor. It is nonetheless useful to incorporate them in addition to true validation statistics, because a model built on a small sample is more likely to be uncertain even if it validates well. For instance, a small sample size could indicate under-sampling of the environment for the species in question, and additional survey effort could place the species in substantially different environments.

Results

Detailed information on models for each species, including full validation statistics and visualizations of occurrence maps and model output is available online (Keinath et al. 2010). Summary validation statistics for each species are presented in Appendix A.

When challenged with holdout datasets, models validated well. The average AUC during cross-validation was high (median across species = 0.85), while the average omission error rate was relatively low (median across species = 0.20). Boyce Index values were lower and more variable (median across species = 0.38), but 85% were significantly and positively correlated with test data, suggesting those models were better than random. Expert reviewers assessed 75% of species as having medium or high-quality models. When combined with dataset size and occurrence data quality, the resulting model quality index ranged from 0.5 to 0.91 with a median value of 0.57. Model quality improved markedly as sample size increased, and incremental model improvement diminished substantially at sample sizes over 100 (Fig. 2a). Model quality also improved with data sets containing higher quality occurrences, though this trend was much less pronounced (Fig. 2b).

Birds had typically larger occurrence datasets than other taxa (Fig. 3a), but sample size for amphibians was similar, and amphibians had generally higher occurrence quality (Fig. 3b). The combination of large and high-quality datasets seemed to result in higher model quality for amphibians (Fig 3c). Small mammals and reptiles (particularly lizards) were poorly sampled (Fig. 4a, b), resulting in a disproportionate number of those species having low-quality models (Fig 4c). Game species had many more occurrences than other groups (Figs. 4a, 5a) though this was not also true for occurrence quality (Figs. 4b, 5b). Species receiving attention under the U.S. Endangered Species Act had generally better occurrence datasets in terms of both quantity and quality (Fig. 5a, b), and therefore had a relatively large proportion of high-quality models (Fig. 5c).

Discussion

Distribution models were generally good, but varied widely in individual model-quality metrics. Poor models were typically associated with lack of suitable species occurrence data (i.e., small sample sizes and/or low quality occurrences). Improvement of these models requires precisely the large-scale biological field effort that prohibits effective management and makes this study necessary. Since such efforts are impossible for the current set of analyses, we incorporated validation statistics into an overall assessment of model quality, which can itself be incorporated into conservation decision-making (Beale and Lennon 2012). It is valuable for wildlife managers to see the best available estimate of distribution for all species, clearly presented with evaluations of model quality that can be used to assess confidence in species-specific results and identify priorities for field survey efforts. Management of species potentially sensitive to development (Chapter 3), but having poor distribution models on which to base assessments of exposure (Chapter 2), could greatly benefit from surveys to increase the sample of high-quality occurrences records, which can then be used to improve estimates of distribution. This is particularly true for groups of species with few occurrences, such as small mammals and reptiles (Fig. 4). To achieve better distribution models, attention must be given to recording and archiving high-quality occurrence data throughout species' suspected ranges (i.e., occurrences where the species is accurately identified, locations are precisely recorded, and supporting documentation is provided).

A second, but equally important, way to improve distribution models is to improve state-wide maps of environmental characteristics. For example, lack of adequate wetlands information hindered distribution modeling for a variety of wetland-associated species. This may be reflected in the lower model quality of birds associated with wetlands when compared to other avian species (Fig 4c), even though the wetland birds had generally larger occurrence data sets (Fig. 4a), although they also tended to have lower quality occurrence data (Fig 4b). Moreover, models for wetland-associated species were often assessed as being of low or moderate quality based on expert review, even though they exhibited validation statistics similar to other groups (Appendix A). Similarly, lack of detailed soil maps hindered modeling the distribution of fossorial mammals, such as pocket gophers, ground squirrels, and pygmy rabbits, while lack of accurate maps depicting vegetation structure hindered modeling of species selecting particular vegetation characteristics that are not prevalent in the Wyoming landscape, such as pinyon-juniper woodland.

Models of evidently low quality should be used with caution, but they can still be useful tools when better information is lacking. For example, even though low-quality models may not provide robust, quantitative depictions of distributions throughout Wyoming, they may provide an informative depiction of distribution in areas of the state that have been adequately sampled. Moreover, models of all quality levels can offer insights into the distribution of otherwise poorly-understood species, possibly providing a mechanism to generate distributional hypotheses that serve as the starting point for field investigations. For example, the model developed for Wyoming pocket gopher served precisely this function. Although it was based on only 15 data points and had a model quality index of 0.44 (less than the median value of 0.57), it helped shift field sampling efforts away from the rocky ridges that were formally thought to be preferred habitat (Thaeler and Hinesley 1979), which ultimately redefined our understanding of the habitat and distribution of this species across its range (Keinath et al. 2014).

Herein I have developed distribution models for all Wyoming's terrestrial vertebrate SGCN. Models were typically good, but quality varied among taxonomic and management groups, largely as a function of the size and quality of occurrence data. Lower quality models should be used with caution, but I used consistent methodologies for all species and explicitly present model quality metrics so managers have an objective sense of model uncertainty when using them in conservation planning, for which they are currently being used (e.g., Chapter 2, WGFD 2010, Germaine et al. 2014, Pocewicz et al. 2014).

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Figures and Tables

Figure 1. Number of Wyoming's Species of Greatest Conservation Need (n = 156) binned into categories based on the proportion of their range mapped due to documented occurrences as opposed to expert opinion of suitable habitat. Species ranges were mapped based on 10-digit hydrologic units (i.e., watersheds) (Keinath et al. 2010) and proportion of range was assessed as the number of watersheds in the species range that contained occurrence records divided by the total number of watersheds in the species range.

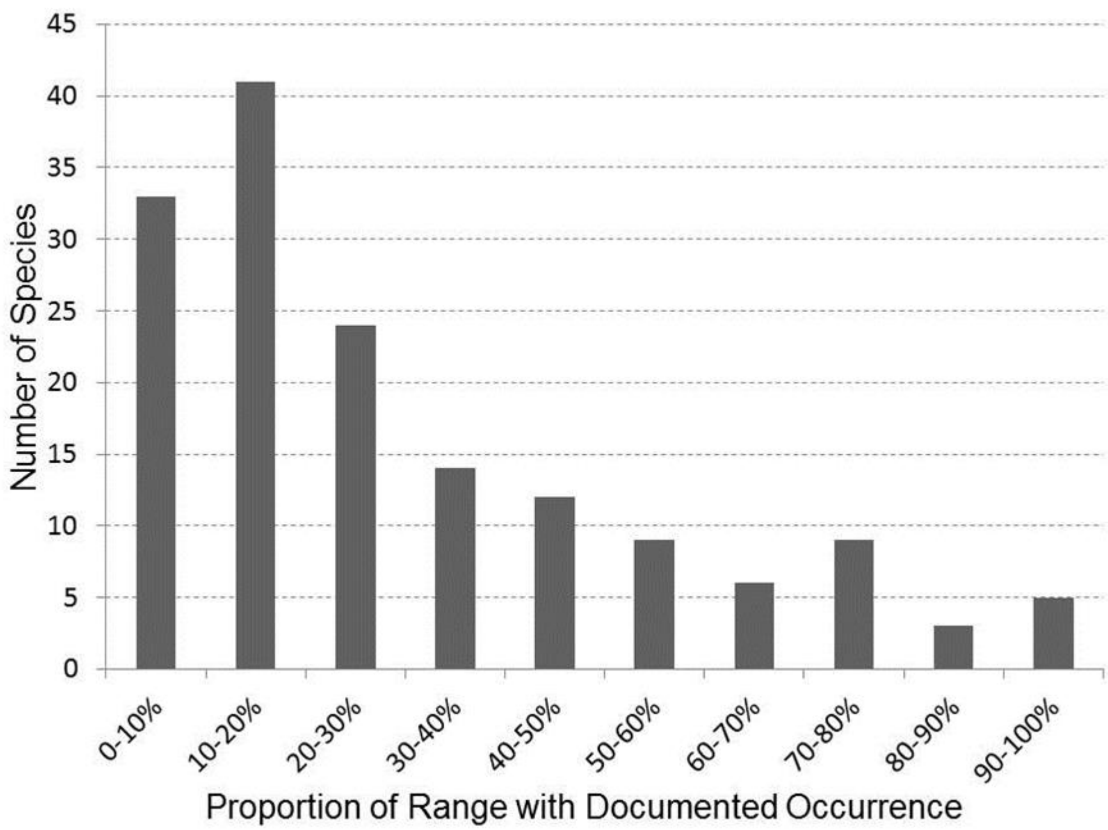

Figure 2. Model quality index as a function of number of occurrences used to build the model (a) and point quality of occurrences (b). Point quality index has been scaled to range from 0 to 1, with higher values representing higher-quality occurrences. Model quality index also ranges from 0 to 1, with higher values representing more robust models. Model quality index was calculated without including component scores for the input occurrence data. Lines are loess smoothing curves.

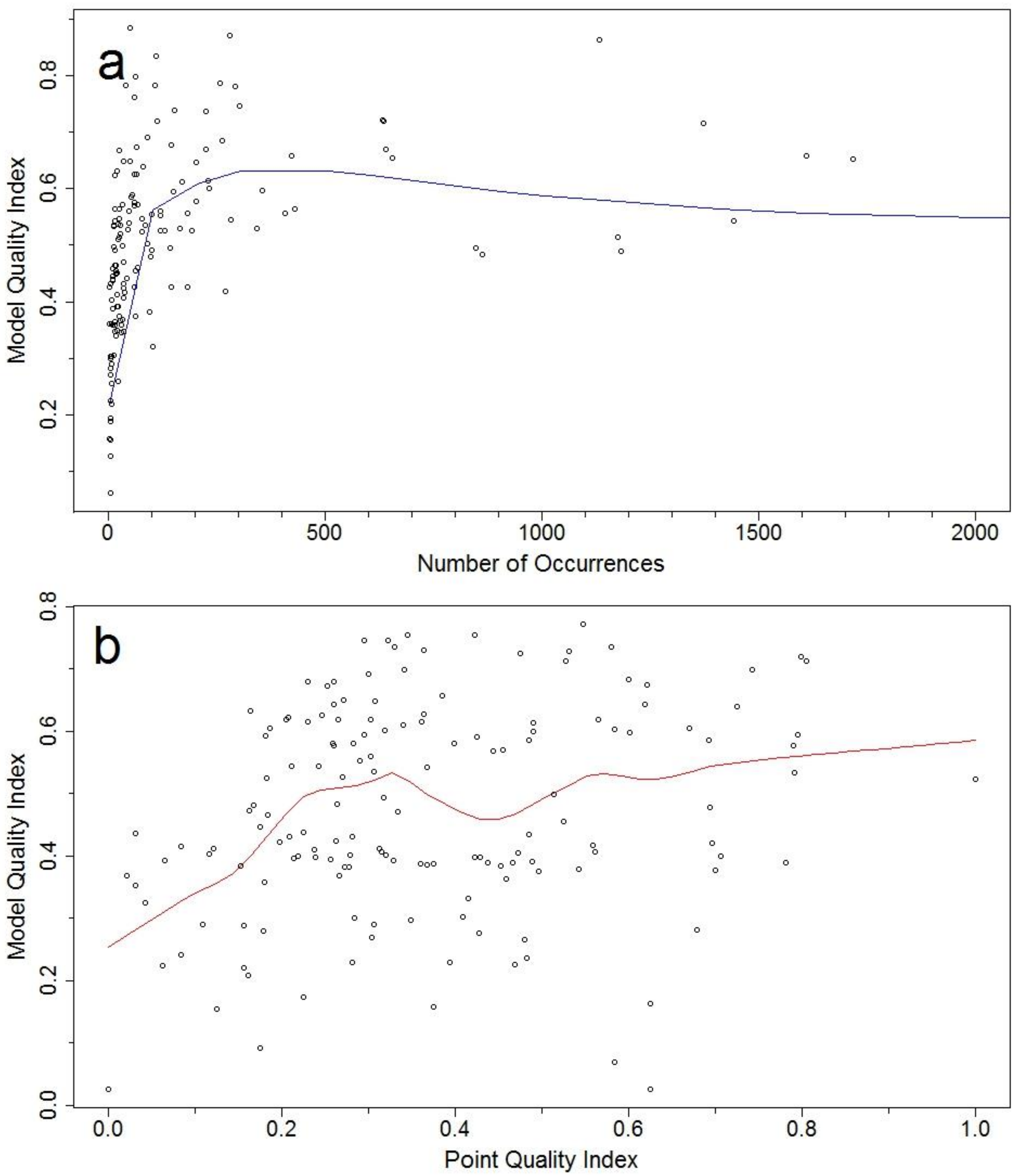

Figure 3. Number of occurrences (a), quality of occurrences (b), and resulting distribution model quality (c) plotted as a function of taxonomic class. Point quality index has been scaled to range from 0 to 1, with higher values representing higher-quality occurrences. Model Quality Index ranges from 0 to 1, with higher values representing more robust models. Model quality index was calculated without component scores for the input occurrence data.

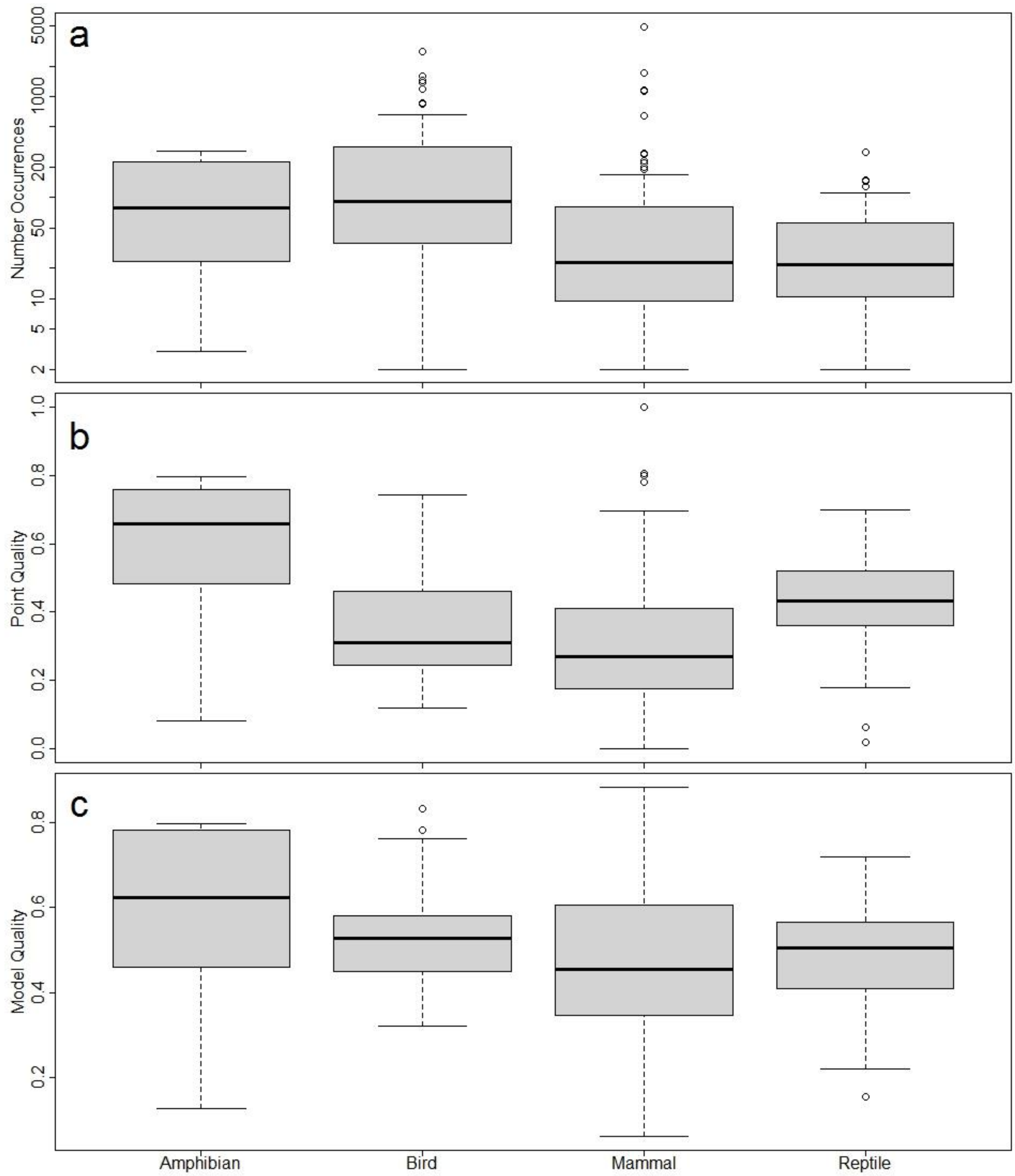

Figure 4. Number of occurrences (a), quality of occurrences (b), and resulting distribution model quality (c) plotted as a function of taxonomic groupings. Game species were addressed separately as they were generally outliers within their taxonomic groups. Taxonomic groups are as follows: Amp = amphibians, B_Rap = raptors, B_Song = songbirds, B_Water = waterbirds, Game = game species, M_Bat = bats, M_Carn = carnivores, M_LagSqu = diurnal small mammals (lagomorphs and squirrels), M_ShrRod = cryptic small mammals (shrews and rodents), R_LizTurt = lizards and turtles, R_Snake = snakes. Point quality index ranges from 0 to 12, with higher values representing higher-quality occurrences. Model Quality Index ranges from 0 to 1, with higher values representing more robust models. For this figure, model quality index was calculated without component scores for the input occurrence data.

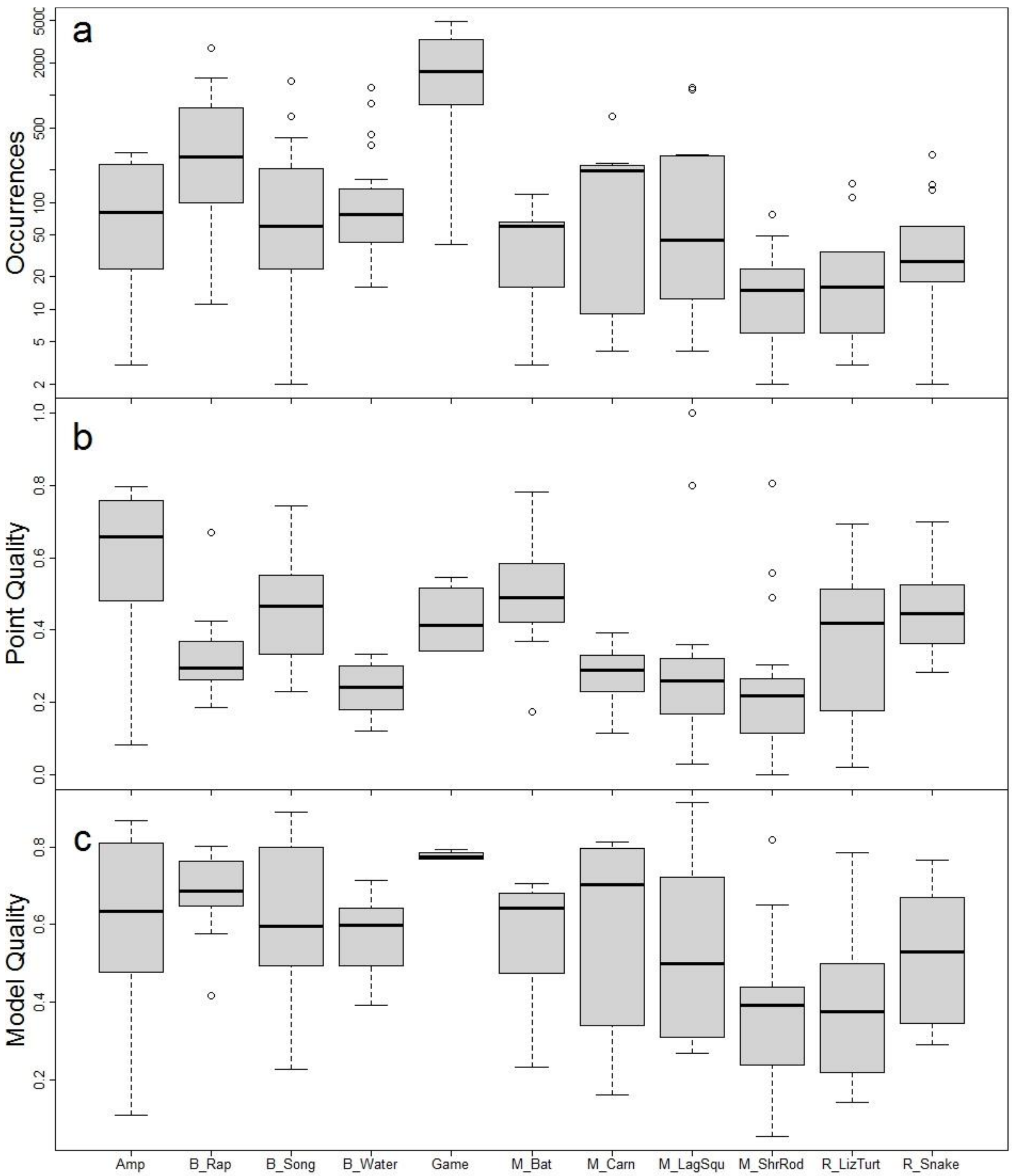

Figure 5. Number of occurrences (a), quality of occurrences (b), and resulting distribution model quality (c) plotted as a function of species management groups. Management groups are as follows: ESA = species petitioned and/or listed under the U.S. Endangered Species Act, Game = species managed by WGFD as permitted game species, General = species listed by WGFD as non-game and not subject to special regulation. Point quality index has been scaled to range from 0 to 1, with higher values representing higher-quality occurrences. For this figure, model quality index was calculated component scores for the input occurrence data.

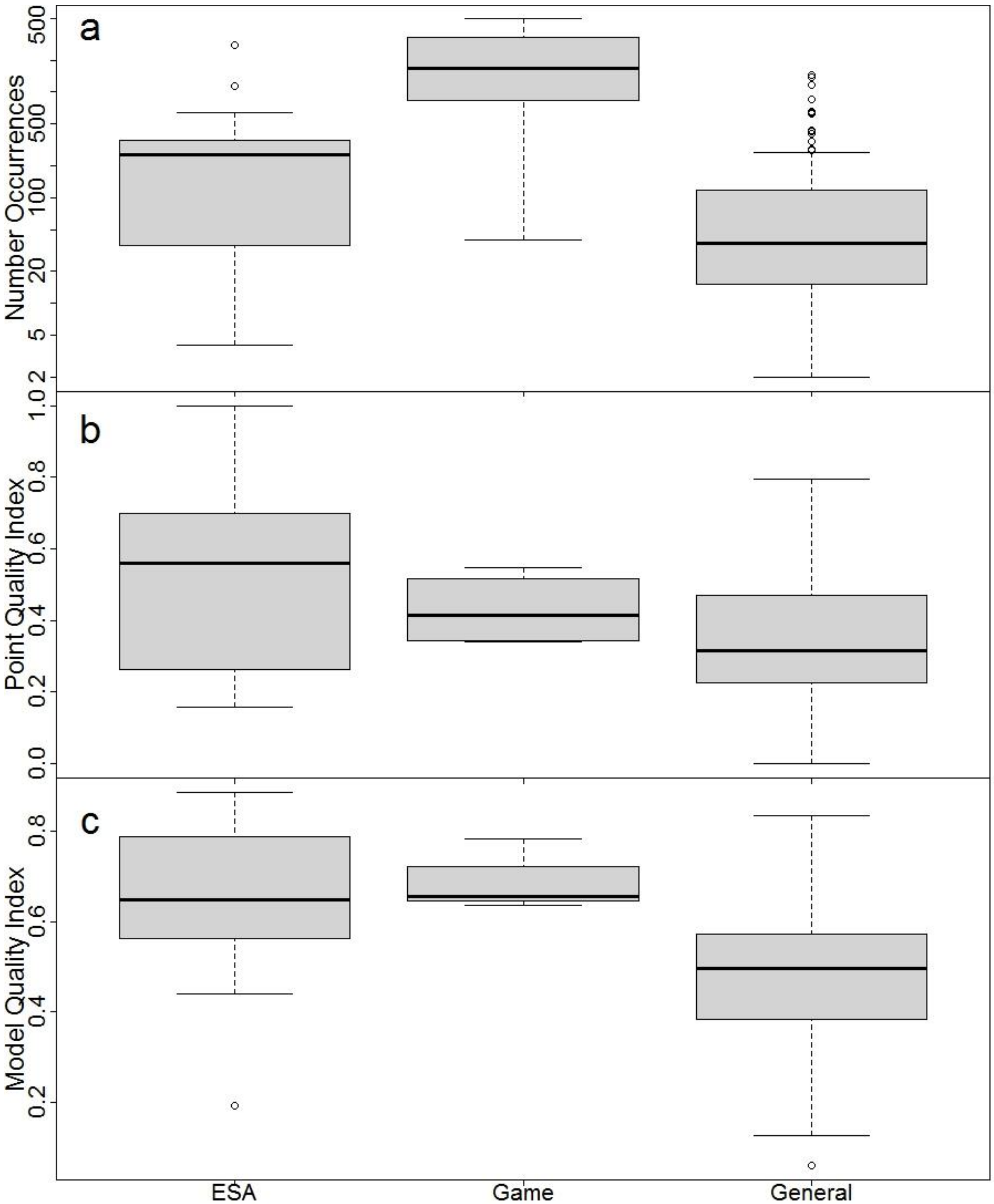

Table 1. Scoring system used to evaluate the quality of occurrence records based on spatial precision (A), date of observation (B), and taxonomic certainty of identification (C).

A. Spatial Precision of Occurrence Record

Score	Definition	Example
4	Location uncertainty ≤ 30 meters	Location via GPS
3	Location uncertainty > 30 meters and ≤ 100 m	Location via 7.5' quad map
2	Location uncertainty > 100 meters and ≤ 300 m	Location via 100k quad map
1	Location uncertainty > 300 meters and ≤ 600 m	Location via large-scale map or detailed written directions
0	Location uncertainty > 600 meters and < ~3,000 m	Location via landscape description (e.g., 5 miles south of Laramie Peak)
U	Record is unusable; uncertainty > ~3,000 m	Museum specimen located by reference to a county

B. Date of Observation

Score	Calendar Year of Observation	Definition
4	≥ 2000	Observation made within roughly 10 years of model creation
3	1990 - 1999	Observation made within roughly 20 years of model creation
2	1980 - 1989	Observation made within roughly 30 years of model creation
1	1960 - 1979	Observation made within roughly 50 years of model creation
0	≤ 1959	Observation made within roughly 100 years of model creation
U	Historic	Record is unusable, because the record is over 100 years old, the species is known to be extirpated from the area in question, or the habitat has changed drastically since its collection.

C. Taxonomic Certainty of Occurrence Record

Score	Category	Definition
4	Confirmed Identification	Adequate supporting information exists within the occurrence record to consider it a valid observation of the species in question
2	Questionable Identification	Supporting information within the occurrence record is insufficient to confirm correct identification of the species (e.g., no supporting documentation or observer credentials), but neither is there any reason to assume that the record is in error
0	Possible Miss-identification	There is reason to believe that the observation could be erroneous. (e.g., extra-limital observation by amateur biologists of species that are easily misidentified)
U	Misidentification	Record is unusable. Information in the occurrence record suggests it is misidentified

CHAPTER TWO

Estimating exposure of wildlife to energy development in the face of rapidly expanding production

Abstract. Maintaining biodiversity in the face of habitat change is exacerbated when national policies, such as the push for energy production, accelerate development and force wildlife managers to initiate conservation with inadequate information. *A priori* species prioritization schemes help alleviate this problem, and while many such schemes have been proposed, all depend on gauging exposure of species to disturbance. Here, we apply a refined, quantitative method to estimate exposure for a wide range of species by calculating the weighted proximity of species' distributions to current and projected energy development footprint. We also incorporate an objective assessment of confidence in these estimates that is often lacking in multi-species assessments. This analysis can be used to assess whether site-specific impacts documented through local studies have the potential to translate into broader population impacts that could, in turn, affect wildlife management priorities. We identify a suite of species (e.g., pygmy rabbit, Wyoming pocket gopher, black-footed ferret, Great Plains toad) that are of concern in our focal landscape when considering conservation activities related to energy development. The methods we employ are widely applicable, using data often available to local and regional management agencies and conservation groups.

Key words: Conservation, Distribution Model, Energy Development, Environmental Impact, Wildlife, Wyoming

Introduction

Habitat change from anthropogenic activities is rapid, extensive, and recognized as the foremost cause of wildlife decline and extinction worldwide (Koh et al. 2004, Vié et al. 2009). Maintaining biodiversity in the face of such change is exacerbated when policies, such as the push for increased and diversified energy production, accelerate development beyond the capacity of wildlife managers to respond. In this situation, managers are forced to rapidly prioritize where to put conservation dollars, and, especially, which species will receive management attention. Such situations are made more difficult when there is a mismatch between the scales of development pressure and conservation management. For example, consider energy development, where national and international demand is driving expansion of energy production, particularly of 'clean' energy sources like natural gas and wind-power. This expanded development has resulted in rapid impacts to local wildlife populations, management of which falls within the purview of state agencies that are ill-equipped to deal with the magnitude of such rapidly increasing disturbance (Naugle 2011). This situation often means that managers can only focus on species once they exhibit widespread declines or if they are politically important. Such efforts are typically conducted on a case-by-case basis (Wainwright and Kope 1999, Vucetich et al. 2006, D'Elia and McCarthy 2010), when what is needed is an effective prioritization that identifies where populations are likely to decline before accumulated habitat loss necessitates drastic intervention (Wilcove and Chen 1998, Drechsler et al. 2011).

To solve this problem, agencies tasked with conservation of species need to prioritize that conservation before populations of those species are heavily impacted. Proposed species prioritization schemes abound (e.g., Metrick and Weitzman 1998, Miller et al. 2006, Joseph et al. 2009, AFWA 2011). The effectiveness of all such schemes hinges upon evaluation of threat, which in turn hinges upon assessment of species-specific levels of habitat alteration. Unfortunately, the rapidity of change often results in a lack of quantitative and taxonomically complete assessments, even for fairly well-studied systems. For instance, Wyoming's State Wildlife Action Plan (SWAP) identified 279 species of greatest conservation need (SGCN), 235 (84%) of which were included due to lack of information necessary for management, the largest component of which is lack of data on distributions (WGFD 2005). Considering the United States as a whole, over 12,000 SGCN have been designated under SWAP programs, with individual states listing 100 to 1,200 species, most of which lack the quantitative information necessary to inform more detailed assessments of habitat disturbance (AFWA 2011). Thus, a critical step in the prioritization process is quantifying the relative exposure of species' habitats to development, which must be accomplished with available, but typically limited, data.

Although spatial impact analysis is fairly well-developed in the realm of strategic environmental assessment (e.g., Geneletti 2013), it is less-often applied in a systematic way to species prioritization, particularly at state levels where much conservation is implemented. Analyses that seek to quantify exposure to development typically occur for particular sites and/or few species (e.g., Johnson et al. 2005, Nielsen et al. 2008, Bennett et al. 2009, Sawyer et al. 2009, Wilson et al. 2011). Quantitative, multi-species, landscape scale assessments of exposure are still rare except at very large scales, and often rely on indicator species or overlays of coarse species range data with broad blocks of proposed development (e.g., Landres et al. 1988, McDonald et al. 2009, De Cáceres et al. 2010). The increasingly sophisticated science of niche modeling can be used to refine exposure analyses, resulting in an effective tool for conservation planning (Sattler et al. 2007, Carroll 2010, Crawford and Hoagland 2010, Hu et al. 2010). None-the-less, few studies make full use of output from such models, generally simplifying analyses by binning results into binary output using standardized, but biologically arbitrary, thresholds (e.g., Carroll 2010, Yackulic et al. 2013). Recent syntheses of human impact studies have resulted in a better understanding of effect distance functions that can also be used to generate quantitative estimates of exposure to development (Copeland et al. 2009b, Benitez-Lopez et al. 2010).

In this study we developed a quantitative estimate of exposure for a wide range of species, while including an objective assessment of our confidence in those estimates – a feature that is often lacking in multi-species assessments. We generated geospatial estimates of habitat suitability and combined them with footprints of energy development anticipated by permitting agencies to develop an estimate of exposure to disturbance for a large number of species across a landscape increasingly influenced by energy development. We use the relative exposure of species, and the estimate rate of increase in that exposure, to assess where conservation efforts could be most fruitful. The methods we employed are widely applicable using data often available to local and regional management agencies and conservation groups, and can thus be adapted to multiple landscapes experiencing different types of disturbance.

Methods

Focal Landscape. Our focal landscape is the state of Wyoming, where there are over 150, mostly poorly-understood SGCN (WGFD 2010). Wildlife management agencies in Wyoming are increasingly overburdened due to a rapidly expanding energy footprint representing 14% of U.S. domestic production (EIA 2011). We focus on petroleum (i.e., oil and natural gas) and wind-power production, both of which alter large tracts of habitat and are rapidly expanding due to strong national support for increased U.S. production of 'clean' energy. The number of petroleum wells and wind turbines in Wyoming has increased drastically in recent years and continued increases of at least 130% and 615%, respectively, are predicted over the next 20 years (Fig. 1b).

Energy Footprint. We constructed development footprints for petroleum (i.e., oil and natural gas) and wind power development in Wyoming at four time periods: 1950, 1980, 2010, and 2030. Maps of past and current infrastructure were obtained from the Wyoming Oil and Gas Conservation Commission (WOGCC 2010) and the U.S. Energy Information Administration (EIA 2011). Future footprints were generated by spatially mapping market projections of energy trends developed for Wyoming (e.g., Stilwell and Crockett 2006, Copeland et al. 2009a). We used active production sites (i.e., operational well pads and wind turbines) as a surrogate for the collection of infrastructure associated with energy development activities, which was necessitated by the fact that production sites were the only energy infrastructure accurately mapped and readily available for all areas of Wyoming across all time periods. At the scale of Wyoming, production sites were a reasonable surrogate for a complete energy footprint, because densities of ancillary infrastructure (e.g., roads, collection facilities, etc.) are directly related to the density and distribution of production sites

We mapped future energy infrastructure by first assessing resource potential across the state (for full details see supplemental online material). For oil and gas potential, we modified a published estimate for the Intermountain West (Copeland et al. 2009a) using higher-resolution data on bedrock geology and geologic faults and more detailed maps of successful wells (i.e., those producing oil or gas) and dry wells (i.e., wells that did not produce) A similar map was generated for wind-power potential using maximum entropy methods (Phillips and Dudik 2008) with currently producing wind-turbines as the response variable and wind-resource potential in combination with topographic position variables as predictors. The resource potential maps were adjusted to reflect spatially-explicit constraints to near-term development that could not be effectively captured in the modeling process (e.g., idiosyncratic legal constraints to development and facilitation of development from existing infrastructure). We seeded the landscape with wells and turbines according to the resource potential maps at rates predicted by energy experts (e.g., Stilwell and Chase 2007) and densities allowed by current legal constraints. Although these predictions were based on the best available market information, we realized that the ultimate extent of energy development depends upon many economic, political and technological factors. Therefore, in addition to the most likely scenario, we also conducted our analyses using a low and high estimate (Appendix B). The results of those analyses changed the overall magnitude of exposure, but had minimal effect on the relative exposure of species, so the remainder of this article focuses on the most likely scenario.

Projecting energy development involves uncertainty that cannot be readily quantified, but we used several means to assess the validity of our prospective energy footprints, all of which indicated good results. We validated the oil and natural gas resource potential map using out-of-bag (OOB) testing techniques to produce ROC AUC (Hanley and McNeil 1982), Cohen's kappa (Cohen 1960), OOB error and overall classification success. All metrics were acceptable (AUC = 0.83, Cohen's kappa = 0.62, OOB error = 22.4%%, overall classification success = 82.5%). Additionally, the rapid pace of development allowed us to use a Spearman rank correlation to test whether our mapped energy potential accurately reflected where producing wells were constructed since we generated the map (Boyce et al. 2002, Hirzel et al. 2006, Petitpierre et al. 2012). Based on 6,240 new wells our energy potential map was highly discriminative (corr coeff = 0.99; $P < 0.001$). We validated the model of wind-power development using ROC AUC and Spearman rank correlations using both a holdout dataset comprising 33% of available data (391 turbines in 8 wind farms), which indicated an acceptable model of wind energy development (AUC of full model = 0.91, correlation based on holdout data = 0.89; $P < 0.001$). Thus, all validation statistics indicated that our representations of future energy development were stable and acceptable.

Final energy footprints were created by buffering infrastructure using a logarithmic decay function where maximum disturbance (Exposure Value; EV = 1.0) occurred near production sites and decayed to near zero at 1 km The impact distance of 1 km was a reasonable estimate derived from the literature (Benitez-Lopez et al. 2010), but species are likely to exhibit differential sensitivities to development, so decay curves of different radii may be appropriate for different taxa. It is precisely this detailed response information that is lacking for most species, thus motivating this analysis. Since taxa-specific adjustments would be speculative, we evaluated all species using identical decay rates. We investigated exposure shifts resulting from the use of different impact distance functions and found they introduced only slight variation in the final results (Appendix B).

Species Distributions. For each SGCN (n = 156 species), we constructed a distribution model using documented occurrences as the response variable and statewide environmental layers representing climate, hydrology, land cover, substrate and terrain as predictor variables (see Chapter 1). We used maximum entropy methods because they have been demonstrated to be accurate and robust under the given data structure, particularly when sample sizes are small (Hernandez et al. 2006, Graham et al. 2008, Wisz et al. 2008, Franklin 2009, Elith et al. 2011, Renner and Warton 2013). To avoid biases associated with opportunistically gathered data (e.g., Johnson and Gillingham 2008, Royle et al. 2012), we used background data selected from the sample set, which covered the entire modeled area (N = 8,000 – 16,000 depending on species), rather than randomly-generated pseudo-absences (Phillips et al. 2009) and employed a randomized, multi-pass filter to select model sets that minimized spatial bias and maximized the quality of occurrences in the final model (Leitao et al. 2011, Kramer-Schadt et al. 2013).

There are highly debated issues with using records of species presence in combination background data to estimate probability of species presence (Royle et al. 2012, Phillips and Elith 2013). As in most situations, the distribution models developed herein cannot approximate true prevalence, which is virtually unattainable with presence-background data (Phillips and Elith 2013). To avoid this pitfall, I do not make this assumption, but rather base estimates of exposure on the 'raw' output of the maximum entropy distribution models, scaled to sum to one over the entire state. This output represents the *relative* similarity of the landscape to locations of known occurrence and does not suffer from the assumptions necessary when trying to approximate probability of species presence (Elith et al. 2011). Exposure estimates derived from these models therefore represent the relative similarity of developed habitats to areas of known presence for species and is a reasonable metric to make comparisons between species; I do not assert that any particular level of exposure represents actual impact to any species. Using such a continuous expression of model output also eliminates the need for selecting a presence threshold for all species, which often results in reduced discrimination and makes calibration of the resulting binary models questionable (Lawson et al. 2014), and for which there is still no good universal rule (Yackulic et al. 2013).

Distribution models varied widely in the quantity and quality of input occurrences, making validation a particularly important issue. Moreover, the paucity of data (i.e., occurrence records) for some species made some models suspect, but these models still represented the best available information, so rather than discarding them we chose to objectively assess our confidence in them and use those confidence estimates to help further inform conservation planning (Beale and Lennon 2012). To avoid biases associated with using any single validation metric, we used several well-supported validation statistics, including area under the receiver operating characteristic curve based on withheld test data (ROC AUC; Hanley and McNeil 1982, Bradley 1997, Liu et al. 2005), predictive success based on 10-fold cross-validation, Spearman rank correlation between modeled similarity and actual presence (e.g., Boyce et al. 2002, Hirzel et al. 2006, Petitpierre et al. 2012), quantitative assessments of input data quality (i.e., age and locational accuracy), and expert review of the final models.

Estimating Exposure to Development. Energy development footprints (where each cell ranged from 0 = no exposure to 1 = complete exposure) were multiplied by the scaled, raw species distribution models (where cells represented relative similarity to other areas of known occupation). The result was summed across Wyoming according to Equation 1, where DM_{si} is the value of the distribution model for species s in cell i, and subscripts og and w represent values for oil/gas and wind development, respectively

$$EI_s = EI_{ogs} + EI_{ws} = \sum_i (EV_{ogi} + EV_{wi}) * DM_{si} \qquad \text{Equation 1}$$

The exposure index for species s (EI_s) represents the degree to which habitats similar to those occupied by the species are proximate to development. EI is therefore near zero for species where developed areas are highly dissimilar those occupied by the species, and would reach a theoretical maximum of 1 if all areas similar to occupied habitat are perfectly coincident with potentially developed sites. The absolute magnitude of EI is not particularly meaningful, but serves as a quantitative way to compare relative exposure between species. For example, a species with EI = 0.3 exhibits twice the potential exposure of a species with EI = 0.15 (Fig. 2).

To assess our confidence in each species exposure estimate, we calculated the EI for each cross validation model of each species and assessed its level of variation by calculating the range of resulting values, dividing the range by the minimum value, subtracting the result from one, and replacing negative values with zero. The resulting fraction ranged from 0 when the range of values of the cross-validated exposure estimates was more than 100% of the minimum value (i.e., highly uncertain EI), to 1 when there was no variation in EI. We used this estimate of variability in EI in combination with model validation statistics to develop a confidence index (CI) for each species (Appendix C), that ranged from 0 for models that validated poorly and resulted in variable estimates of EI, to an upper limit of 1 for models that validated well and resulted in stable estimates of EI.

Results

Species varied in both the expected magnitude and rate of increase in their exposure to energy development (Fig. 1, Appendix C). This ranking held even in the face of large variations in our level of confidence for each species, because species with the highest exposures tended to have highly discriminative models (Fig. 3). The majority of species in our study showed sufficiently low exposure to current and future energy development that effects on populations of those species are not likely even with substantial uncertainty in where the species occurred. Generally speaking, montane obligates showed very low exposure (e.g., Fig. 4B: fisher, $Es < 0.001$), while species restricted to low and mid-elevation basin shrublands and grasslands showed high exposure (e.g., Fig. 4C: Great Plains toad, $Es = 0.278$). Several species were predicted to exhibit accelerated exposure in the future (e.g., Fig. 1A: black-footed ferret = 613% increase over current levels; pygmy rabbit = 105%; Wyoming pocket gopher = 75%).

Exposure to petroleum infrastructure was larger than to wind turbines (Fig. 5, Appendix C), but petroleum and wind-energy footprints were largely non-overlapping (Fig. B2), resulting in spatially extensive disturbance from the combination of the two types of energy development. Despite its comparatively small footprint, wind power represented more than half the calculated exposure to energy development for 14 species. Of particular note, exposure of federally-listed back-footed ferret was driven largely by wind power (Fig. 4E: Eswind = 0.177, Espetroleum= 0.004), which lead to its ranking as the 6th most exposed species in our study.

Discussion

Species with a larger proportion of their habitat coincident to development have a correspondingly greater potential for population-level impacts (Naugle 2011). Herein, we quantified this relative exposure. Sixteen of Wyoming's SGCN had EI values higher than Greater Sage-grouse (*Centrocercus urophasianus*), for which impacts from development have been extensively investigated (Fig. 5, Appendix C). To our knowledge very few of these species are currently the focus of research or conservation relative to this exposure, although many of them probably should be. This is particularly true when species demonstrate biological sensitivities that suggest exposure is likely to translate into impacts (e.g., Cardillo et al. 2005). For example, our analysis suggested pygmy rabbit (*Brachylagus idahoensis*) will be highly exposed to energy development, and pygmy rabbit has known biological sensitivity stemming from restrictive habitat specificity that has already resulted in placing one sub-species on the U. S. endangered species list due to habitat disturbance (USFWS 2010). Similar arguments can be made for other highly-exposed species in our analysis, notably Wyoming pocket gopher (*Thomomys clusius*), black-footed ferret (*Mustela nigripes*), and Great Plains toad (*Anaxyrus cognatus*). Eventual decisions regarding conservation priorities will necessarily involve additional factors (e.g., cost, logistics, social concerns, political climate; Miller et al. 2006), but species with relatively high exposure may be worthy of increased scrutiny.

Three additional factors that we are able to evaluate with quantitative exposure analysis suggest that a small set of Wyoming's mammal species may be of particular concern. First, species with restricted distributions, and thus little capacity to spatially avoid development, are generally at higher risk from habitat alteration than others (e.g., Owens and Bennett 2000). This raises concern for species like black-footed ferret and Wyoming pocket-gopher (Fig. 4e, f) relative to more widely distributed basin species (e.g., Fig. 4a). In fact, the global distributions of these species are so restricted that conservation for the species as a whole will likely hinge upon conservation in Wyoming. Second, large projected increases in exposure over current levels suggests that proactive conservation could have a greater potential to effect change, because efforts enacted now could avert impacts rather than mitigating damage to already impacted populations (Wilcove and Chen 1998, Drechsler et al. 2011). Pygmy rabbit and black-footed ferret are notable in this regard, because they are predicted to experience large increases in exposure (Fig. 1). Also, together with black-tailed prairie dog, these two species exemplify a third factor of concern, namely that projected exposure is concentrated in areas predicted as most suitable (i.e., areas that are more likely to be occupied), which may suggest a greater potential for impact (e.g., Fig. 6). Conservation action for species having exposure caused by intensive development in areas highly-similar to occupied habitat (e.g., Pygmy Rabbit or Black-footed Ferret) will likely be different than for species where exposure is due to larger portions of their distribution overlapping less-intense development (e.g., Wyoming Pocket Gopher or Great Plains Toad). In particular, the former might benefit greatly from site-specific conservation action (e.g., conservation easements or retirement of mineral rights) targeted toward core areas of distribution, similar to the approach taken for Sage Grouse. In contrast, the latter might require more broad-scale mitigation in the form of development stipulations (e.g., avoiding key habitat features wherever development occurs).

The use of umbrella species has long been a dominant approach to multi-species conservation despite ambiguous scientific support (e.g., Ozaki et al. 2006, Branton and Richardson 2011). This is true of our focal landscape, where the role of Greater Sage-grouse as a purported umbrella species (Rowland et al. 2006) has contributed to intense conservation attention, culminating in an executive order in Wyoming to restrict new energy development in areas identified as 'core' sage-grouse habitat (Fig. 7). Our exposure analysis shows that complete cessation of future development in core areas would reduce predicted exposure of the 25 most-exposed species by an average of only 7% (Fig. 8). None-the-less, our analysis suggests the sage-grouse core area strategy can substantially mitigate impacts for a few species. Notably, 30% of exposure for the federally-endangered black-footed ferret, which is not generally viewed as falling under the sage-grouse umbrella, can be averted by precluding wind turbines in a relatively small area identified as core sage-grouse habitat. Similarly, anticipated exposure of pygmy rabbit to oil and gas development can be reduced by up to 20% with strict conservation of large-stature sagebrush in sage-grouse core areas. For other species sage-grouse core areas will not mitigate exposure to energy development, but could offset exposure by providing a refuge if a large proportion of those species' undeveloped habitats are coincident with sage-grouse core areas. In this context, limiting development in core areas may be effective for species like pygmy rabbit and black footed-ferret, which have close to half their distribution within core areas (Fig. 7). In contrast, species like Wyoming pocket gopher and Great Plains toad have sufficiently small portions of their distribution within sage-grouse core areas that they are unlikely to benefit from core area policies.

A benefit of our comprehensive, quantitative approach to examining exposure is that it does not focus solely on species with plentiful data and political support, but assesses all species on the same scale and explicitly identifies deficiencies, thus allowing a more transparent assessment of risk. Relative confidence in exposure estimates is useful in this context and should be considered when assessing potential conservation targets and identifying next steps. Based on our estimates of relative exposure and our confidence in those estimates, we view species as falling into one of three heuristic categories; low exposure, high exposure, or equivocal exposure (Fig. 3). Most species in our study clearly have low exposure to energy development, even in the face of low confidence, and thus are not urgent candidates for energy-related research or conservation. Species with large exposure values in combination with relatively high confidence in the exposure estimate (e.g., Great Plains toad, pygmy rabbit, Wyoming pocket gopher, greater sage-grouse) fall into the high exposure category and are logical targets of immediate conservation attention and/or intensive research to quantify and mechanistically understand local impacts that could translate into population-level effects (e.g., Walker et al. 2007, Arnett et al. 2008, Gilbert and Chalfoun 2011). Finally, species with sufficiently low confidence relative to exposure could be considered equivocal, because there is a distinct concern that the exposure estimate hinges upon our inability to accurately map their distribution (e.g., black-footed ferret). Next steps for these equivocal exposure species would logically involve resolving distributional uncertainties through additional field survey efforts before conducting more rigorous studies of local impacts. However, in these cases it must be recognized that, if the present level of exposure is already of a magnitude that declines have occurred, future distribution mapping efforts could be confounded by those declines.

Rapid expansion of anthropogenic development is a global concern, but impacts to wildlife are initially felt at local and regional levels, and it is at these geographic scales where management is typically implemented. Precautionary wildlife management suggests that we use available, though sometimes imperfect, information to prioritize conservation efforts so we can minimize the potential for costly, reactionary responses once impacts have reached obviously critical levels. Formal, quantitative exposure analysis, which we demonstrated here, can facilitate proactive conservation planning for the many understudied species for which wildlife managers are responsible. It is important to stress, however, that we do not suggest basing long-term policies solely on this analysis. Rather results from quantitative exposure analysis serve to better inform conservation prioritization schemes and impact assessments. Once exposure analysis has helped reduced the list of species of greatest concern to a manageable level, the logical next step is to identify areas for immediate protection while conducting targeted research to understand the biological vulnerability of individual taxa, reduce uncertainties, and inform the design of appropriate long-term conservation strategies. While our work has focused on energy development in Wyoming habitats, the approach we outlined could be easily employed to gauge threat exposure in other settings. In particular, while we have focused on energy development, spatial development models for agriculture, forest loss, or urban expansion could similarly be used to predict exposure to other threats, and thus to better inform how scarce conservation resources should be best used.

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Figures and Tables

Figure 1. Changes through time in exposure to energy development for 156 Species of Greatest Conservation Need (SGCN) in Wyoming (A) relative to the cumulative number of oil and gas wells (B; solid line) and wind-power turbines (B; dashed line). Several species mentioned in the text are highlighted in colors that match those in Fig. 2. Data on energy infrastructure were compiled from sources listed in Appendix A.

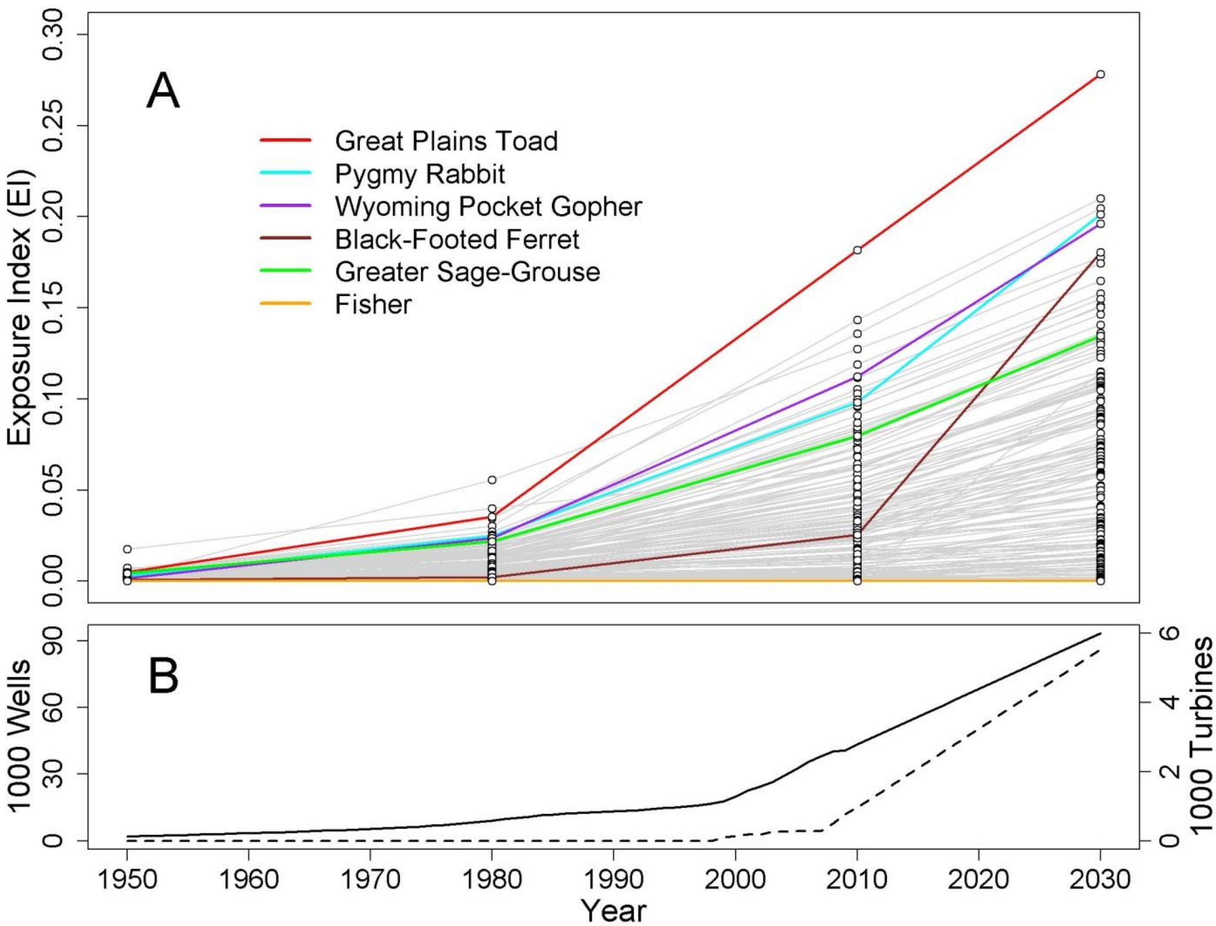


Figure 2. Examples of Exposure Index (EI) values presented with equivalent densities of structures (wells or turbines), average inter-structure distances, and remotely sensed images of approximately equivalent areas of Wyoming's landscape (B-F). Approximate well locations shown as red dots. Equivalent well distances and densities were calculated assuming a 1-kilometer footprint and uniform well spacing across a landscape where all habitat is identical. Locations of images are shown on a county map of Wyoming (A).

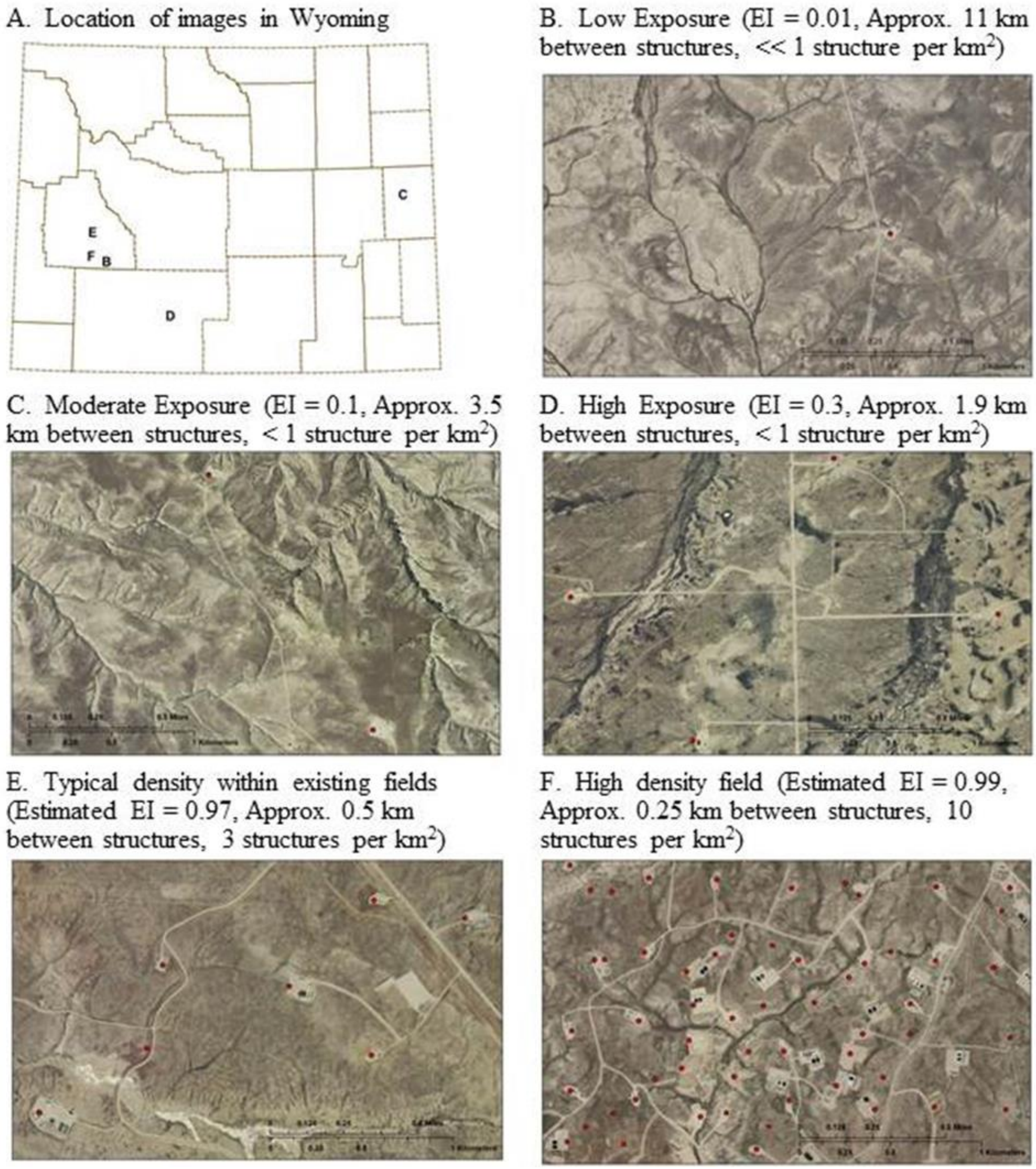


Figure 3. Joint distribution of exposure index (EI) and confidence index (CI) for 156 SGCN in Wyoming. Higher EI values indicate greater exposure to development, while higher CI values indicate more confidence in the exposure estimate. Species mentioned in the text are highlighted in colors matching those in Fig. 1. Gray text highlights heuristic zones of concern discussed in the text (boundaries subjective).

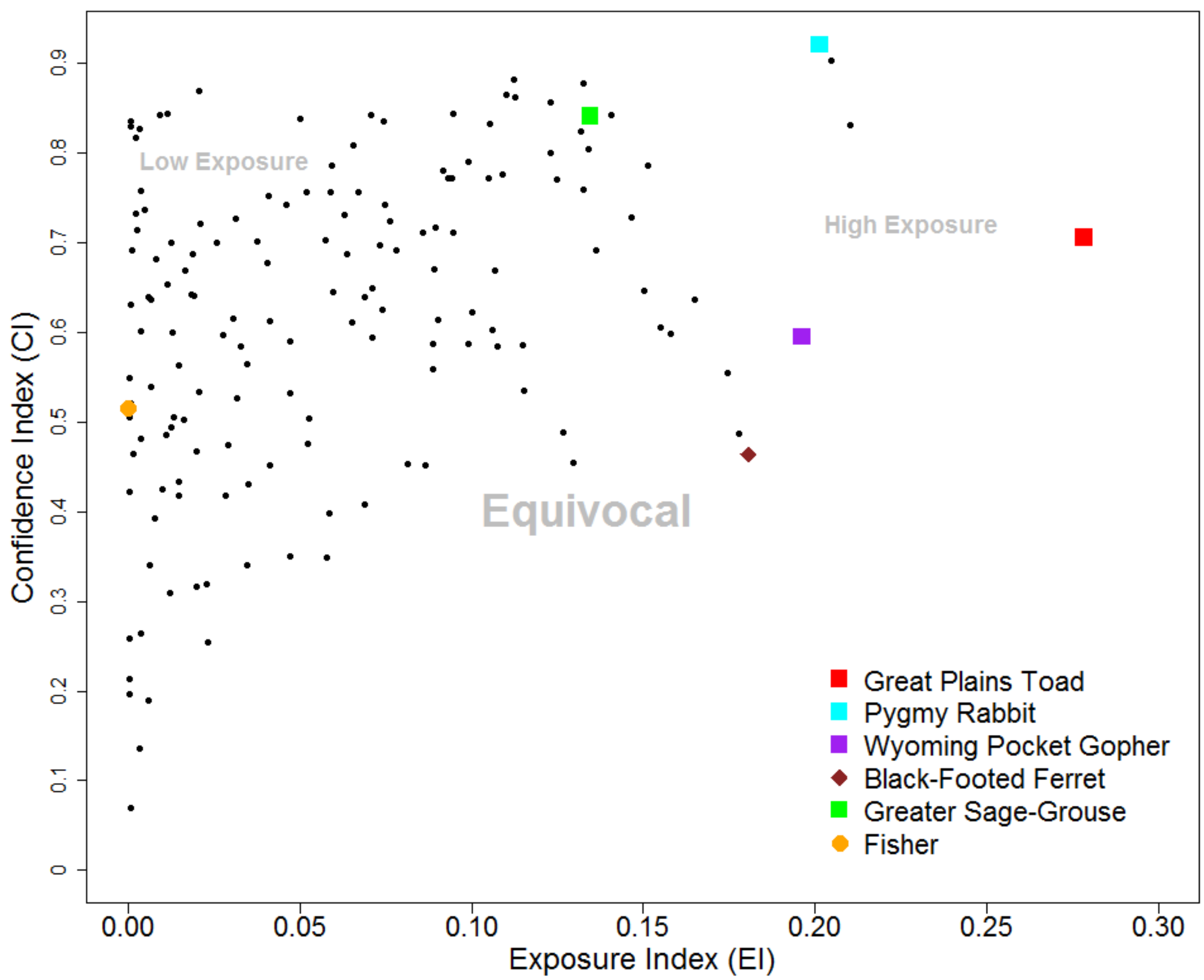


Figure 4. Wyoming distribution maps for the six Species of Greatest Conservation Need (SGCN) highlighted in Figs. 1 and 3 superimposed on energy development projections for 2030. Black shading represents the footprint from oil and gas development and blue represents the footprint from wind-power development. Red shading represents the area of predicted occurrence for greater sage-grouse (A; EI=0.135), fisher (B; EI<0.001), Great Plains toad (C; EI=0.278), pygmy rabbit (D; EI=0.201), black-footed ferret (E; EI=0.181), and Wyoming pocket gopher (F; EI=0.196). The latter species is endemic to Wyoming, so the model represents its entire global distribution. Background is a topographic relief map of Wyoming with county boundaries for reference.

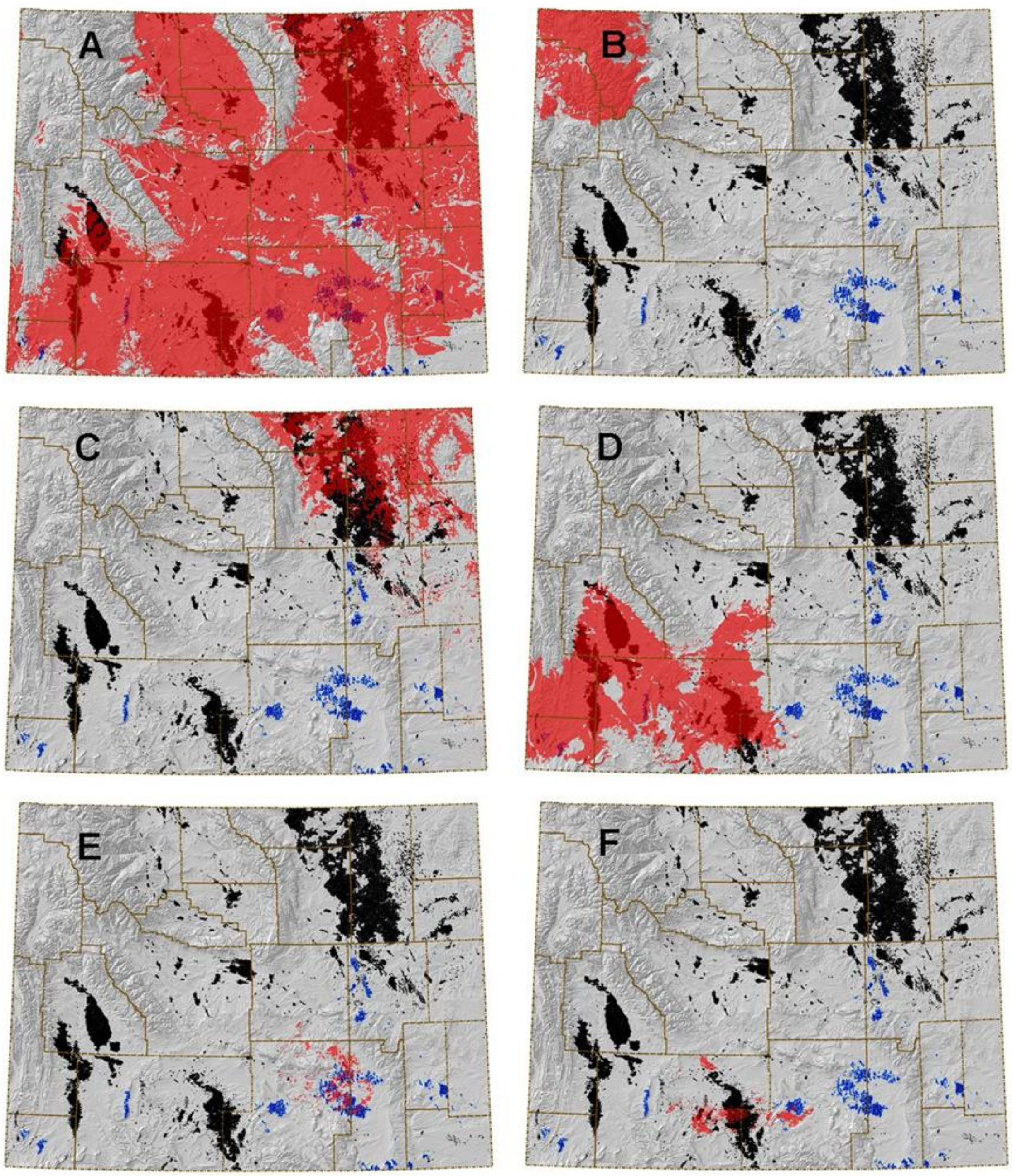


Figure 5. Projected 2030 total Exposure Index (EI) for 156 Wyoming Species of Greatest Conservation Need (SGCN) examined in this study. Ordinate shows individual species (codes provided in Appendix BBB) ordered by their exposure rank using the 1-kilometer exposure curve. Grey portions of bars represent the proportion of EI due to wind-power development; white portions represent EI due to oil and gas development, error bars represent range in total estimated EI obtained by using all cross-validation models. Panels A-D show different subsets of the 156 species analyzed.

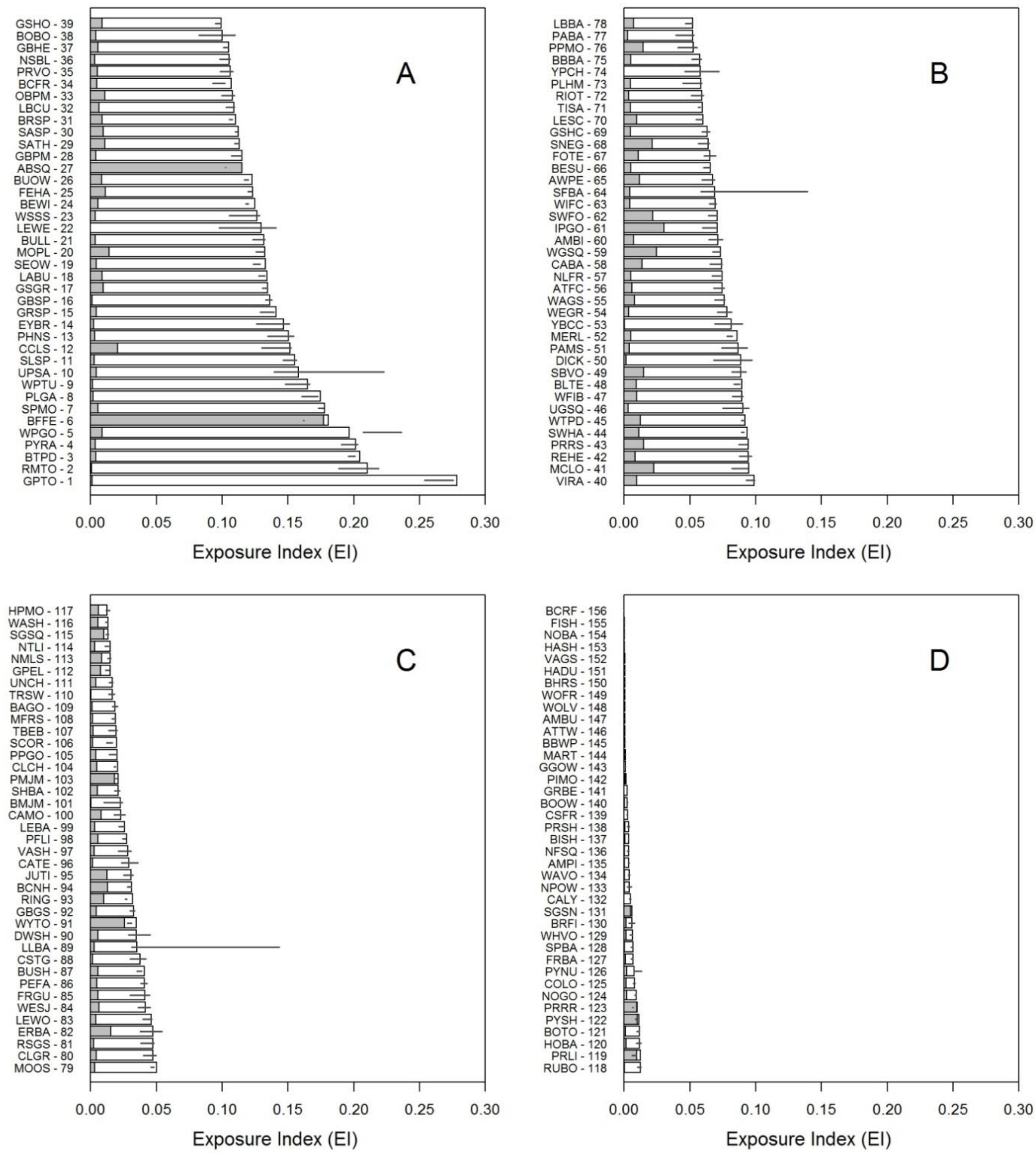


Figure 6. Distribution of exposure relative to modeled habitat for several Wyoming Species of Greatest Conservation Need (SGCN) with high Exposure Indices from energy development. Horizontal axis shows quantiles of habitat above a binary threshold maximizing test success, where the 100% quantile represents habitat most similar to sites of known occupation. Vertical axis shows the proportion of habitat falling within 1 kilometer of an oil or natural gas well or wind-power turbine based on 2030 projections. Colors reflect those in Figures 1 and 3.

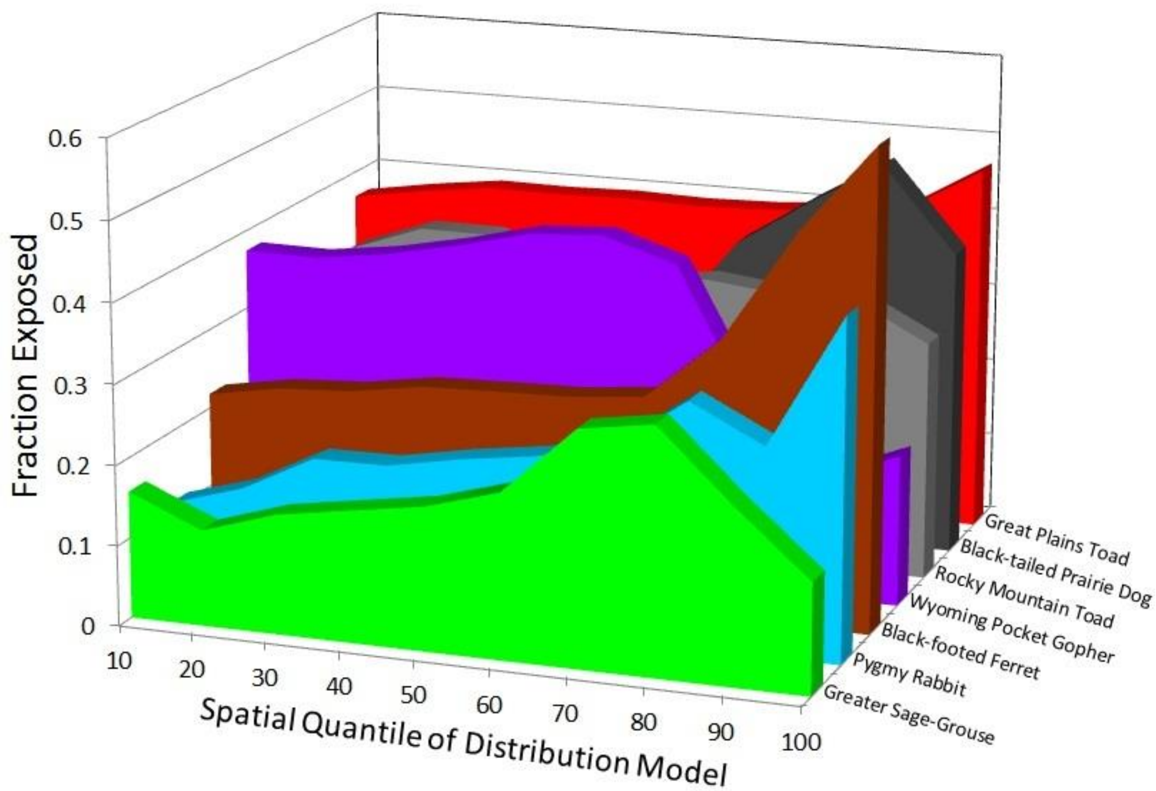


Figure 7. Map of Greater Sage Grouse 'core areas' (green shading) as defined by Wyoming Executive Order 2011-5. Also displayed are the 2030 predicted exposure surface for oil and gas wells and wind-power turbines, a shaded topographic relief map, and county boundaries.

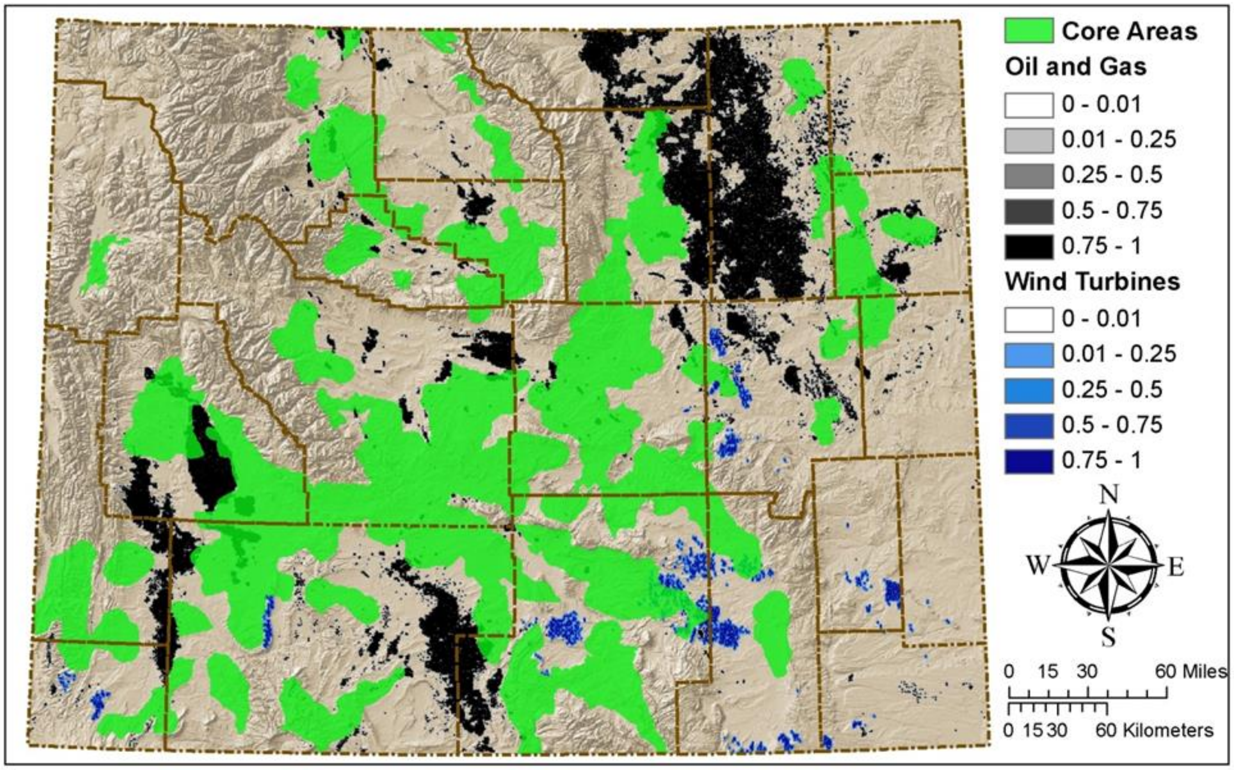
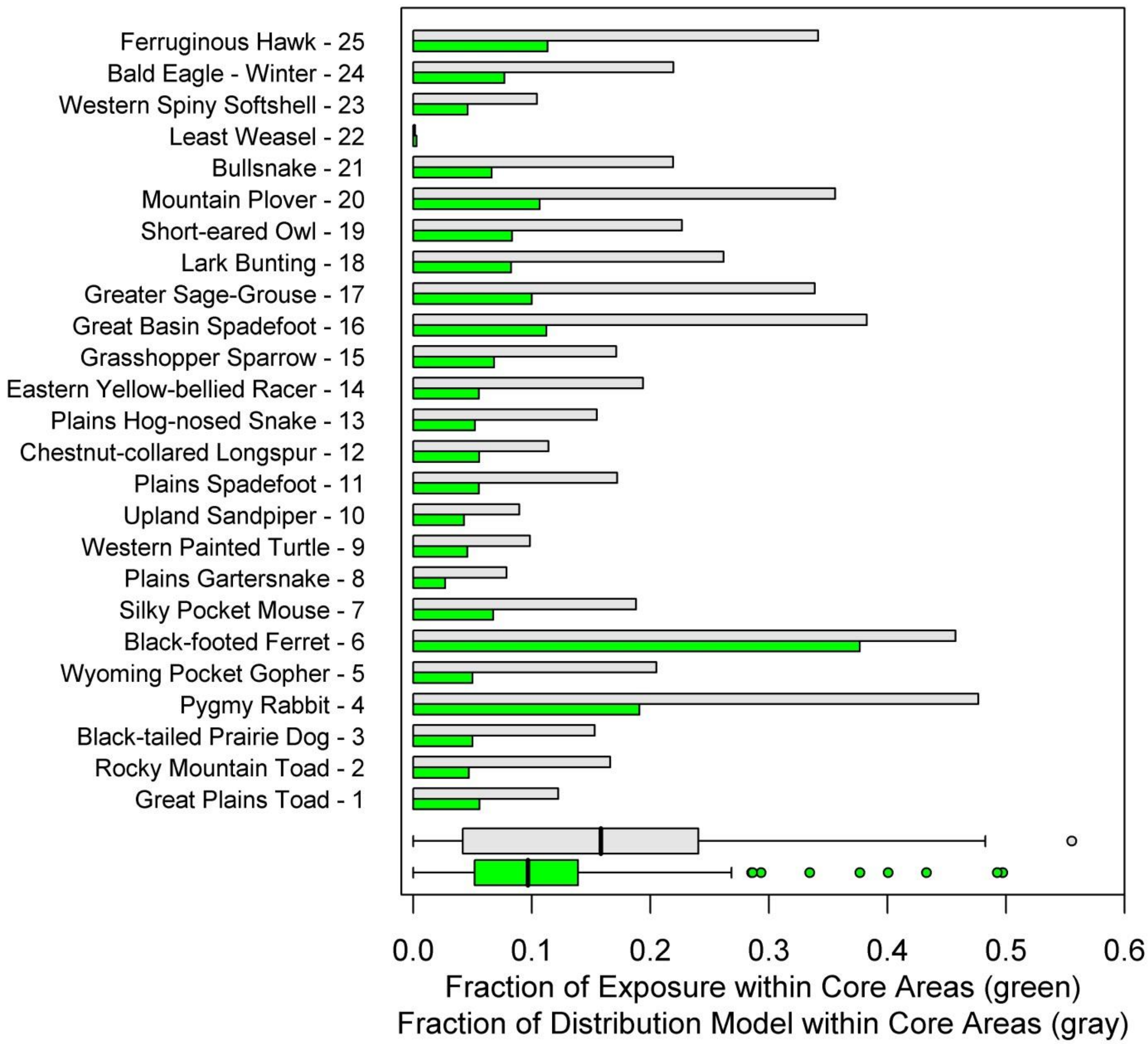


Figure 8. Fraction of the total 2030 Exposure Index (EI; green) and distribution model values (gray) falling within core areas of Greater Sage-Grouse. Bars represent the 25 most-exposed species in our study. Box plots represent a synthesis of all 156 species. Note that these values are best-case figures that assume a complete cessation of all development in core areas. The actual core area policy limits certain types of development but does not prohibit them.



CHAPTER THREE

A global analysis of species sensitivity to habitat disturbance using local data

Abstract. Elucidating patterns in species-specific responses to disturbance is an important focus of modern ecology and conservation. Most species response studies have been geographically local (and thus idiosyncratic), taxonomically narrow, or used indirect response variables such as IUCN Red List categories. Factors influencing sensitivity to population disturbance likely differ from those influencing global endangerment. We investigated which landscape and species characteristics explained species persistence (presence/absence) after local disturbance using studies from around the world on all four terrestrial vertebrate classes, allowing direct comparisons across taxa. We used generalized linear mixed-effect models to assess the combination of factors that best explained persistence in remnant patches across 77 post-disturbance studies (n = 3,342 habitat patches, n = 1,559 species). We explicitly considered interactions in an information-theoretic approach and thereby distinguished characteristics that affected species sensitivity (i.e., the response to patch size) from those that influenced overall probability of presence on the landscape. In concordance with island biogeography theory, the size of remnant habitat patch was the most important driver of species persistence. Across all classes, habitat specialists, carnivores, and larger species were less prevalent in remnant habitat patches, but those effects were substantially modified by interactions. Sensitivity differed among taxonomic classes, with reptiles being particularly sensitive, and was influenced primarily by habitat type and specialization (and to a lesser degree by fecundity, lifespan, and body mass). Grassland species occurred in a lower proportion of patches, with forest and shrubland species being more sensitive. Habitat specialization generally increased sensitivity, though amphibian specialists appeared less sensitive. Habitat relationships were more important than life-history characteristics (e.g., reproductive output, body mass) in mediating persistence following disturbance. Habitat specialization increased sensitivity to disturbance and interacted with class and habitat type; forest specialists and habitat-specific reptiles were particularly sensitive. Frontline conservation of biodiversity often occurs at relatively local scales, and our results suggest local conservationists faced with habitat-altering disturbances should pay particular attention to habitat specialists, especially reptiles. Our results also clarify the need to distinguish the risk factors for sensitivity to disturbance from those influencing probability of presence in the landscape.

Key words. Vulnerability, mammal, bird, reptile, amphibian, conservation planning, extinction likelihood, biodiversity, macroecology, patch size, island biogeography, habitat

Introduction

In terms of species conservation, sensitivity can broadly be defined as the degree to which species respond to external stressors, with more sensitive species exhibiting larger responses than less sensitive species. Variation in species sensitivity to disturbance translates directly to their probability of decline, endangerment and ultimately extinction. Although the effects of disturbance on individual species are complex (Purvis et al. 2005), ecological specialization (e.g., habitat use or diet; Sekercioglu 2011, Bregman et al. 2014, Newmark et al. 2014), reproductive capacity (Polishchuk 2002), geographic range (Davidson et al. 2009), population density (Newmark 1991), and body size (Cardillo et al. 2005) all appear particularly important predictors of species sensitivity. These characteristics are not independent of each other (e.g., population density is clearly related to body size), and they may affect extinction probably in interactive ways. None-the-less, their use to inform conservation planning has become commonplace, as have broad generalizations regarding specific relationships (e.g., species with low reproductive output are more sensitive).

In large part, generalizations regarding species sensitivity have been derived from studies over large geographic areas (e.g., continental or global) of broad taxonomic groups using surrogates of species endangerment as a response variable (e.g., Purvis et al. 2005, Cardillo et al. 2008, Davidson et al. 2009). The most common of these surrogates is the conservation status rank developed by the International Union for Conservation of Nature (IUCN) for its Red List of Threatened Species (IUCN 2014). Although information from such broad studies is applied to local and regional conservation, many studies exploring species sensitivity have also occurred at a local level (e.g., particular forests or management areas) investigating subsets of local fauna that track population responses to specific stressors. Despite the temptation (and need) to generalize relationships between species characteristics and sensitivity, the factors important over broad areas and pertaining to the endangerment of species likely differ from those important locally and pertaining to the decline or extirpation of populations. This is evidenced by the fact that local studies often yield different conclusions than broad studies regarding which species characteristics are important (Fig. 1). For instance, ecological specialization seems to be an important predictor of sensitivity in local studies (Fig. 1c), whereas body size and distributional patterns appear be more important in broad studies (Fig. 1b,c). Further, regardless of scale, studies often disagree regarding the direction of their effect on sensitivity. For example, of the studies finding a significant effect of ecological specialization on sensitivity, roughly half find that specialization increases sensitivity, while the other half find that it decreases sensitivity or has mixed effects (pie charts in Fig. 1c).

The disparate response between broad studies pertaining to species endangerment compared to local studies pertaining to the decline or extirpation of populations could be methodologically induced, or it could indicate biologically meaningful differences. In either case, this conflicting information poses a challenge for wildlife managers when making conservation decisions. Because conservation is often enacted by local and regional resource managers, results of local studies would seem to be more applicable to conservation planning. Unfortunately, local studies are often of limited generality because they have narrow biogeographic scope and explore highly specific characteristics that are difficult to extrapolate to other areas and other taxa. Further, managers must make decisions between disparate taxa (e.g., amphibians, birds, mammals and reptiles), which have never been assessed comparably in sensitivity studies. The goal of our study was to address this gap by conducting a global analysis of species responses to local-scale disturbance across a broad range of taxa and landscapes, providing a framework for generalizing how diverse wildlife will be differentially affected by such disturbance.

Herein, we conduct a meta-analysis based on a database of studies compiled from around the world that documented the presence and absence of species in remnant habitat patches following disturbance events, which is an empirical measure of local extirpation that is a direct measure of sensitivity to disturbance. We incorporated these studies into a single, unified analysis that was global in scope and included all classes of terrestrial vertebrates. Thus, we conducted a broad analysis based upon local data rather than indirect assessments of extinction risk (see also Newbold et al. 2013, Benchimol and Peres 2014, Quesnelle et al. 2014). We hypothesized that a suite of species characteristics (Fig. 1) would influence sensitivity to local disturbance. More specifically, we predicted that characteristics defining species ecology (e.g.,

Fig. 1C; habitat specificity, trophic level) would be more important in predicting species responses than general life history characteristics often deemed important in broad studies (e.g., body size, reproductive potential). Unlike previous studies based on local data, our inclusion of multiple taxonomic classes facilitated broad comparison across disparate species. Additionally, the breadth of our analysis allowed us to explicitly consider interactions between local landscapes and species characteristics, which are likely to be important (Purvis et al. 2005), but have rarely been tested in a generalizable way.

Methods

Scope and Data. We compiled data from studies that documented the presence and absence of terrestrial vertebrate species in patches of native habitat remaining after fragmentation events (Appendix E). We drew roughly half the studies from those compiled by Prugh et al. (2008), to which we added studies from a Web of Science™ search for titles containing keywords "patch, fragment or remnant" AND "species, community, diversity, or richness" AND "bird, avian, mammal, amphibian, reptile, herp*, or wildlife". We filtered search results by focusing on relevant subject categories (e.g., ecology, biodiversity conservation) and eliminating studies that did not incorporate multiple habitat patches, did not document the presence and absence of individual species in all patches, or for which raw data were not available in the published article or directly from the authors.

We developed a set of characteristics describing each study landscape and each focal species (Table 1). Landscape characteristics were obtained from the study area descriptions in the articles containing species presence and absence data (Appendix E). Although many species characteristics have been evaluated for their influence on sensitivity, we focused on a set that has been widely addressed in the literature, was available for most species, and could be effectively generalized across disparate taxa. We obtained avian life history data from Bird Life International (2013) and Sekercioglu (2012), with additions from the Handbook of the Birds of the World series (Del Hoyo et al. 2011). Mammal data were drawn from the Pantheria database (Jones et al. 2009), with additions from primate data maintained by the authors (e.g., Deaner et al. 2007). Most amphibian and reptile data, as well as supplementary data for mammals and birds, were drawn from the studies containing species presence and absence data, IUCN Red List accounts (IUCN 2014), the AmphibiaWeb database (Lannoo 2005, AmphibiaWeb 2013), the Animal Diversity Web database (Myers et al. 2013), the Encyclopedia of Life database (Parr et al. 2014), and primary literature. Additional demographic data for all species were obtained from the Animal Aging and Longevity database (Tacutu et al. 2013). Body size for reptiles and amphibians was generally reported as snout-to-vent length, so we used published relationships to covert these values to body mass (Lagler and Applegate 1943, Blakey and Kirkwood 1995, Deichmann et al. 2008, Meiri 2010, Feldman and Meiri 2013). A complete set of variables influencing fecundity (i.e., age at first reproduction, litters/clutches per year, litter/clutch size, and maximum life span) was not available for all species. We used simple linear regressions to estimate missing values based on body size within taxonomic order and family, which yielded generally good predictions ($r^2 = 0.71 \pm 0.18$ SD; Appendix F). We log-transformed all continuous variables to correct for skewness and conducted tests of variable collinearity; no two variables had a Pearson's correlation coefficient greater than 0.49.

Analysis. We evaluated the influence of landscape and species characteristics on species occurrence in remnant patches using generalized linear mixed-effect models. All analyses were conducted in R version 3.1.1 (R Development Core Team, http://www.r-project.org) using the glmer function in the lme4 package to fit models (Bolker 2014) and the glmulti package

(Calcagno 2014)to conduct model selection in an information theoretic framework (Burnham and Anderson 2002). When comparing models, we varied only fixed effects (Bolker et al. 2009, Muller et al. 2013). We guarded against over-fitting by limiting model complexity to 12 terms at each step and comparing competing models using Bayes Information Criterion (BIC; Burnham and Anderson 2004, Muller et al. 2013, Aho et al. 2014). Models were deemed well-supported if they had BIC weights within 10 percent of the top model, and variables were included in subsequent analysis if they had a cumulative BIC weight greater than 0.5 over the resulting confidence set (Burnham and Anderson 2004, Johnson and Omland 2004).

There were many variables with literature support to consider in our models, and little rationale for specifying particular combinations of interactions in the candidate set of models. Further, given the large number of variables, it was not possible to exhaustively compare combinations and their interactions. We therefore used a step-wise process to construct an optimal model. All candidate models at each step included taxonomic class and patch size as fixed effects, because they were of primary interest in our analysis, and study as a random factor, to control for inter-study variation. First, we identified important landscape characteristics by comparing models that differed only in combinations of landscape fixed effects and their interactions. Second, we selected important species characteristics by comparing models that differed only in combinations of species fixed effects and their interactions. Third, with important landscape and species variables thus identified, we compared models differing only in interactions between those variables and the base model (i.e., interactions with patch size and taxonomic class). Fourth, we compared models that differed only in combinations of interactions between the landscape and species variables. To create an optimal model, we combined the terms identified as most important at each of these steps (Appendix G).

To synthesize and present the results of the optimal model, we first evaluated the importance of individual parameters by running the model on a centered and scaled dataset. Coefficients from this scaled model indicated the magnitude of effect for each term on the overall probability of presence in a patch, and thus the relative strength of different main effects and interactions. These coefficients represent key predictors of species prevalence in disturbed landscapes. We were particularly interested in interactions with patch size, because they indicated differential sensitivity to degrees of habitat loss that were independent of the inherent rarity of species on the landscape. Therefore, for variables that significantly interacted with patch size, we calculated the peak proportional change in the relationship between probability of presence and patch size (i.e., maximum slope in plots of probability of presence against area divided by the area-specific prediction; see Fig. 4 for illustration). Peak proportional change was independent of actual amount of habitat, which varied across species and landscapes, and thus provided a convenient way to compare sensitivity to habitat reduction among disparate species. Thus, the coefficients of our optimal model indicated drivers of species prevalence in disturbed landscapes, while the peak proportional changes in probability of presence from variables that interacted with patch size indicated drivers of species sensitivity to disturbance. This distinction between probability of presence and sensitivity was and important dimension of our analysis and is maintained through the remainder of this chapter.

Previous studies have shown that treating species as independent data points may increase the risk of bias and Type I errors, because species characteristics may not be independent of phylogeny (Freckleton et al. 2002, Bradshaw et al. 2014). In contrast, other studies have found that the results of trait-based analysis can be largely unchanged by phylogenic consideration (Newbold et al. 2013). In our case, accounting for phylogeny was particularly problematic, because a well-resolved phylogeny that is consistent across all four taxonomic classes in our study is not currently available. In order to evaluate the potential importance of phylogeny in our results, we replicated our final model with taxonomic Family as an additional random variable and compared the results to those without additional taxonomic information.

Results

The final dataset included 77 studies from around the world (Fig. 2, Appendix E) that documented the occurrence of 1,559 species across 3,342 habitat patches, resulting in 65,695 records of patch-specific presence and absence. Avian species (n = 924) represented the majority of the compiled data, followed by mammals (n = 330), reptiles (n = 166) and amphibians (n = 139). Studies in forest ecosystems (n = 57) were more common than those in shrublands (n = 11) or grasslands (n = 9).

Model selection (Appendix G) yielded a final model containing 4 landscape characteristics, 7 species characteristics, and 13 interaction terms (Fig. 3). There were no differences in interpretation caused by including additional taxonomic data (Appendix H). Absence of taxonomic influence suggests that results were not biased by lack of quantitative phylogenetic information, so we based the remainder of our results and discussion on the non-phylogenetic analysis. The final model demonstrated a fair fit to the data, with an area under the curve (AUC) from the receiver operating characteristic curve of 0.77 and a true positive classification rate (TPR) of 0.68 based on a threshold that maximized training sensitivity plus specificity. Cross-validation suggested this fit was robust, because models built by removing one study were able to predict presence of species in patches of the withheld study with similar accuracy (AUC = 0.66 ± 0.12, TPR = 0.65 ± 0.12; mean ± SD).

When considering the overall probability of presence in patches following disturbance, patch size had the largest main effect, with species more likely to be present in larger patches (Fig. 3). Landscape characteristics included main effects with the second and third largest absolute values: habitat type (grassland species were less likely to be present) and landscape size (species assessed over larger landscapes were less likely to be present). Main effects of some species characteristics also had a large influence. In particular, amphibians and reptiles were less likely to be present than other classes, and habitat specialists were less likely to be present than generalists. Carnivores, larger species, and species with larger litter sizes were less likely to be present, while species with longer life spans and more litters per year were more likely to be present. Many interaction terms had marginal effects, but several were comparable in size to the main effects they modified. Notably the interaction between taxonomic class and species habitat specificity substantially influenced probability of presence, with amphibian specialists more likely to persist in remnant habitat patches than other classes and non-specialists (Fig. 3). The effect of litter size was markedly different between classes, where amphibians and mammals with larger litters had markedly higher probabilities of presence than either birds or reptiles.

Several variables affected sensitivity to habitat patch size, as assessed by peak proportional change in probability of presence (e.g., Fig. 4). These variables included habitat type, taxonomic class, habitat specialization, litter size, life span, and body mass, all of which had significant interactions with patch size in the optimal model (Fig. 3). Species in forest and shrubland were more sensitive to changes in patch area than those in grasslands (Fig. 4). Species with a high degree of habitat specificity were more sensitive than either generalists or moderately specialized species, and reptile habitat specialists were the most sensitive collection of species in the study (Fig. 5d). Although amphibian habitat specialists were more sensitive to changes in patch size than non-specialists, they were still less sensitive than generalists of the other classes (Fig 5). Compared to habitat type and habitat specialization, the effects of life history traits (i.e., life span, litter size, and body mass) were relatively small, although large body size increased sensitivity in mammals as much as habitat specialization (Fig. 5c).

Discussion

Remnant patch size was a key driver of species prevalence in disturbed landscapes, which reinforces the notion that the amount of habitat loss is of paramount importance in predicting species responses (Watling and Donnelly 2006, Prugh et al. 2008). Species characteristics had notable effects on probability of presence and on sensitivity to remnant patch size, with characteristics defining ecological relationships (e.g., habitat type in combination with specialization) being consistent drivers. Habitat specialization, often in combination with other life history parameters, was largely related to species being both rare in the landscape and sensitive to disturbance (Fig. 6). Habitat specialists were generally less prevalent across landscapes, and thus more likely to be absent in remnant patches. They were also more sensitive than generalists to changes in the amount of available habitat (i.e., the proportional change in their probability of occurrence with increasing patch size was greater; Fig. 5). This pattern lends support to the idea that habitat specialists may be particularly impacted by land-altering disturbance and should in turn receive heightened conservation attention in such cases (Matthews et al. 2014).

The sensitivity of habitat specialists, however, must be considered with respect to taxonomic class, as evidenced by the interaction that we observed between habitat specificity and taxonomic class (Fig 3). Reptiles exhibited the lowest probability of presence following disturbance across habitat remnants and showed the highest sensitivity to patch size among the classes, which was further increased by habitat specificity (Fig. 5d, Fig. 6). Our results thus indicate that reptiles are particularly sensitive to habitat disturbance. This finding accords with recent analyses indicating that negative responses of reptiles to habitat loss have increased more than those of other taxa in the face of climate change (Mantyka-Pringle et al. 2012) and may help explain pronounced global declines in reptiles (Gibbons et al. 2000, Böhm et al. 2013). Amphibians had low and variable probability of presence (Fig. 6), but contrary to expectations, this increased with habitat specialization (Fig. 3), and amphibians showed lower sensitivity to patch size than other taxa (Fig. 5a, Fig. 6). In other words, despite amphibians being more likely to be absent across all patch sizes, amphibian habitat specialists seemed more capable of persisting in small patches relative to generalist species. Although not intuitive, this finding agrees with evidence suggesting that amphibians are relatively more likely to be impacted by habitat loss at larger patch sizes (Mantyka-Pringle et al. 2012). We hypothesize that the generally lower prevalence of amphibians may result from amphibians being particularly affected by large-scale stressors (e.g., climate change, disease; Collins and Storfer 2003), so local effects of habitat change tend to occur against a backdrop of widespread population declines (Houlahan et al. 2000). It is also possible that the apparently low sensitivity of amphibians in this analysis is because their presence depends more on whether the existing patch mosaic has maintained connectivity between their aquatic and terrestrial life forms than coarse metrics such as patch size (Becker et al. 2007). These differences between classes highlight the importance of using a multi-taxon approach to analysis of species sensitivity, as we have done.

We found that forest species were the most sensitive to habitat fragmentation (Fig. 4). This sensitivity was, however, only moderately greater than that of shrubland species. Thus, in terms of species response to habitat disturbance, shrublands could be considered more similar to forests than grasslands. By comparison, grassland species had a consistently lower probability of presence across a range of patch sizes, but were less sensitive to changes in patch size (Fig. 5, Fig. 6). In other words, species in forests and shrublands had a relatively low probabilitiy of presence at small patch sizes that increased with increasing patch size, while species in grasslands had a low probability of presence that did not change with patch size (i.e., species sensitivity to patch size was lower in grasslands). The consistently low prevalence of grassland species across a range of patch sizes accurately reflects widely-observed declines of grassland species resulting from habitat loss and degradation (Hill et al. 2014). Further, we suspect that the low sensitivity of grassland species demonstrated here may underlie the results of studies investigating fragmentation in grasslands, wherein even grassland specialists often show mixed responses to habitat fragmentation and degradation (Benson et al. 2013).

Conservation of biodiversity in the face of habitat disturbance generally occurs at relatively local scales. In this context, generalizable patterns in the response of species to local disturbance are likely to be more applicable for conservation planning than those derived from broad studies. Herein we presented a broad analysis of local data that demonstrates the complex interaction of species and landscape characteristics that influence response of wildlife to habitat disturbance. Our results further stress that conservationists should pay particular attention to habitat specialists, notably habitat-specific reptiles and forest specialists, when considering suites of species potentially affected by habitat loss and disturbance (Fig. 6). Moreover, after decades of searching for cross-taxa generalities, our work reveals important differences among taxa in how they respond to habitat loss, dependent upon habitat specialization and life history.

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Figures and Tables

Figure 1 Results of studies investigating the ability of species traits to predict sensitivity, where studies were compiled from a standardized Web of Science search (Appendix D). While local studies generally use local declines as their response variable (black shading; e.g., abundance trends), broad studies more often use synthetic risk scores (gray shading; e.g., IUCN Red List categories). Species' body size and range size tend to be more commonly important in broad studies that use risk scores as their response variables (a, b), whereas ecological specialization tends to be more important in local studies (c). Despite being a widely-accepted predictor of sensitivity, measures of reproductive potential have mixed support at both scales, with most studies showing non-significant effects (d). In contrast, rarity is broadly supported at all scales of analysis (e). Direction of effect for significant results are displayed in pie charts as the proportion of studies where the trait was shown to increase sensitivity (+), decrease sensitivity (-) or have a complex effect (~).

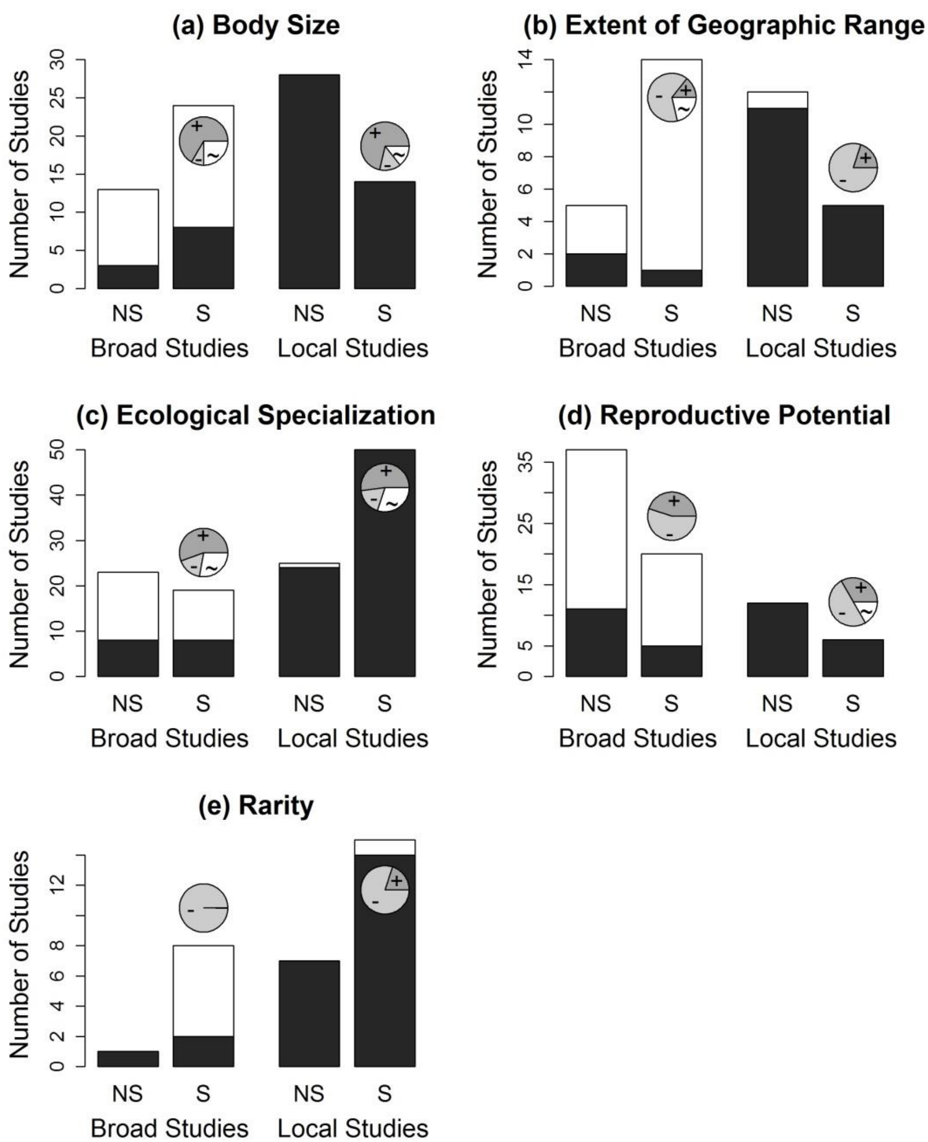

Figure 2 Map of the studies used in this meta-analysis, displayed with their habitat type and taxonomic focus.

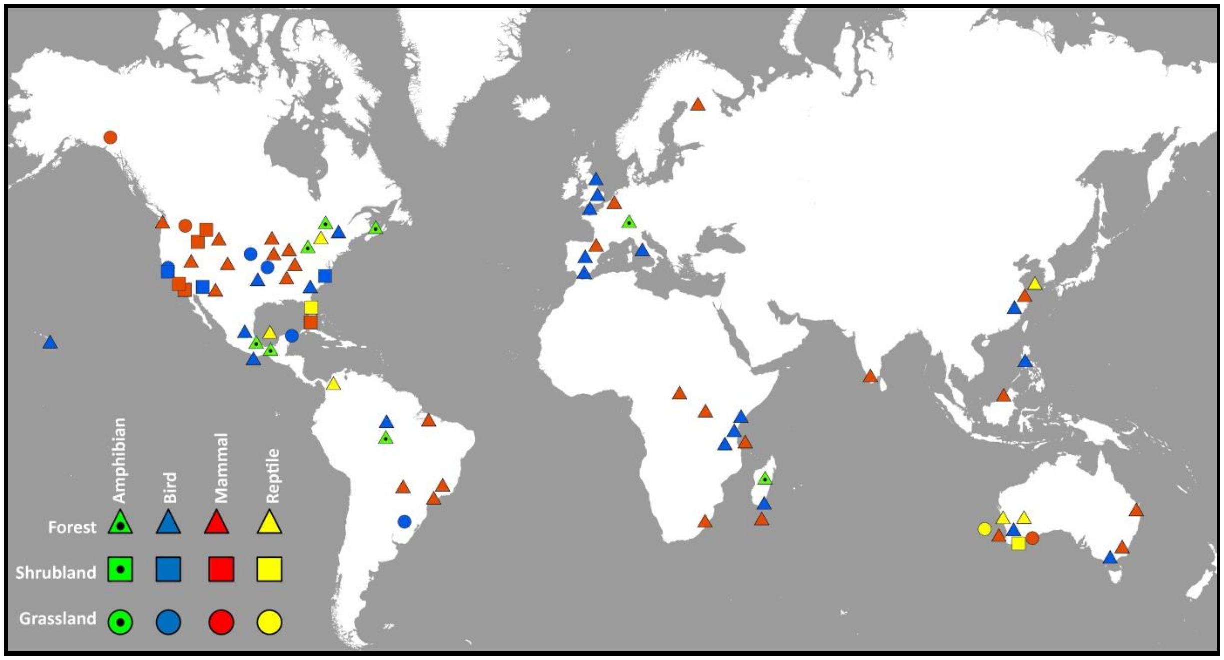

Figure 3 (next page). Effect sizes, standard errors, and significance levels for terms in the optimal model predicting patch occupancy as a function of scaled landscape and species characteristics. Significance is noted on the vertical axis (*** = P < 0.001, ** = P < 0.01, * = P < 0.05). Reference values for factors are specified by "(ref)" and are displayed with an effect size of zero. All variables influence probability of presence, while interactions with patch size are drivers of sensitivity (see Fig. 4 for illustration).

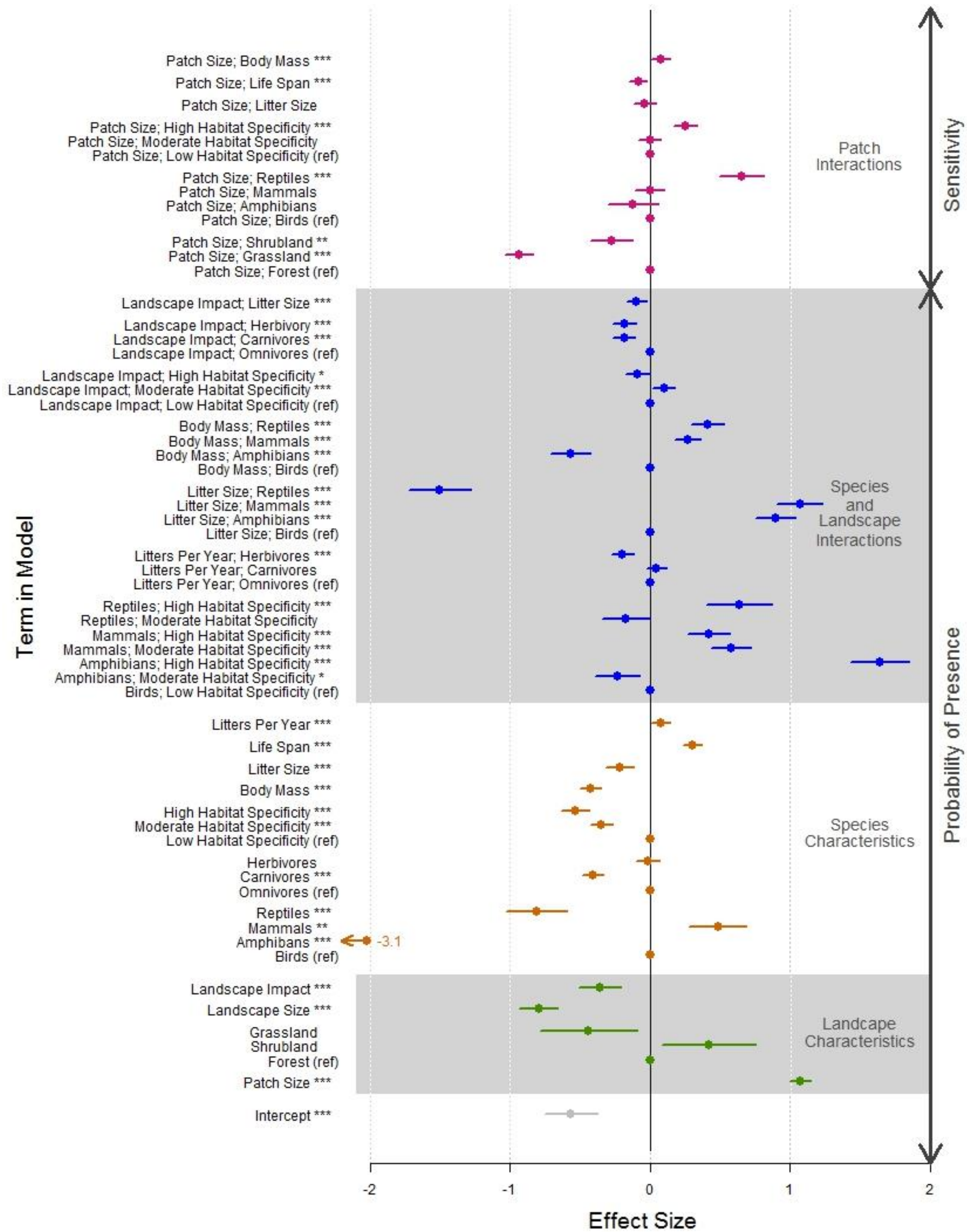
Patch Size; Body Mass ***
Patch Size; Life Span ***
Patch Size; Litter Size
Patch Size; High Habitat Specificity ***
Patch Size; Moderate Habitat Specificity
Patch Size; Low Habitat Specificity (ref)
Patch Size; Reptiles ***
Patch Size; Mammals
Patch Size; Amphibians
Patch Size; Birds (ref)
Patch Size; Shrubland **
Patch Size; Grassland ***
Patch Size; Forest (ref)
Landscape Impact; Litter Size ***
Landscape Impact; Herbivory ***
Landscape Impact; Carnivores ***
Landscape Impact; Omnivores (ref)
Landscape Impact; High Habitat Specificity *
Landscape Impact; Moderate Habitat Specificity ***
Landscape Impact; Low Habitat Specificity (ref)
Body Mass; Reptiles ***
Body Mass; Mammals ***
Body Mass; Amphibians ***
Body Mass; Birds (ref)
Litter Size; Reptiles ***
Litter Size; Mammals ***
Litter Size; Amphibians ***
Litter Size; Birds (ref)
Litters Per Year; Herbivores ***
Litters Per Year; Carnivores
Litters Per Year; Omnivores (ref)
Reptiles; High Habitat Specificity ***
Reptiles; Moderate Habitat Specificity
Mammals; High Habitat Specificity ***
Mammals; Moderate Habitat Specificity ***
Amphibians; High Habitat Specificity ***
Amphibians; Moderate Habitat Specificity *
Birds; Low Habitat Specificity (ref)
Litters Per Year ***
Life Span ***
Litter Size ***
Body Mass ***
High Habitat Specificity ***
Moderate Habitat Specificity ***
Low Habitat Specificity (ref)
Herbivores
Carnivores ***
Omnivores (ref)
Reptiles ***
Mammals **
Amphibans ***
Birds (ref)
Landscape Impact ***
Landscape Size ***
Grassland
Shrubland
Forest (ref)
Patch Size ***
Intercept ***
-3.1
Patch Interactions
Species and Landscape Interactions
Species Characteristics
Landcape Characteristics
Sensitivity
Probability of Presence
Term in Model
-2
-1
0
1
2
Effect Size

Figure 4 Relationship between probability of presence and sensitivity to remnant patch size across habitat types. (a) Grasslands exhibited lower probability of presence, or a lower proportion of patches with species present. (b) The probability of presence of species in forests (solid line) and shrublands (dashed line) changed markedly with patch size, but far less so in grasslands (dotted line). (c) The proportional change in probability of presence (i.e., slope of lines in Fig. 4b divided by the predicted value) typically showed a peak value (dots) that we used as a measure of sensitivity to changing habitat area. Grassland species therefore exhibited lower sensitivity than either forest or shrubland species, as shown by a smaller maximum proportional change in probability of presence.

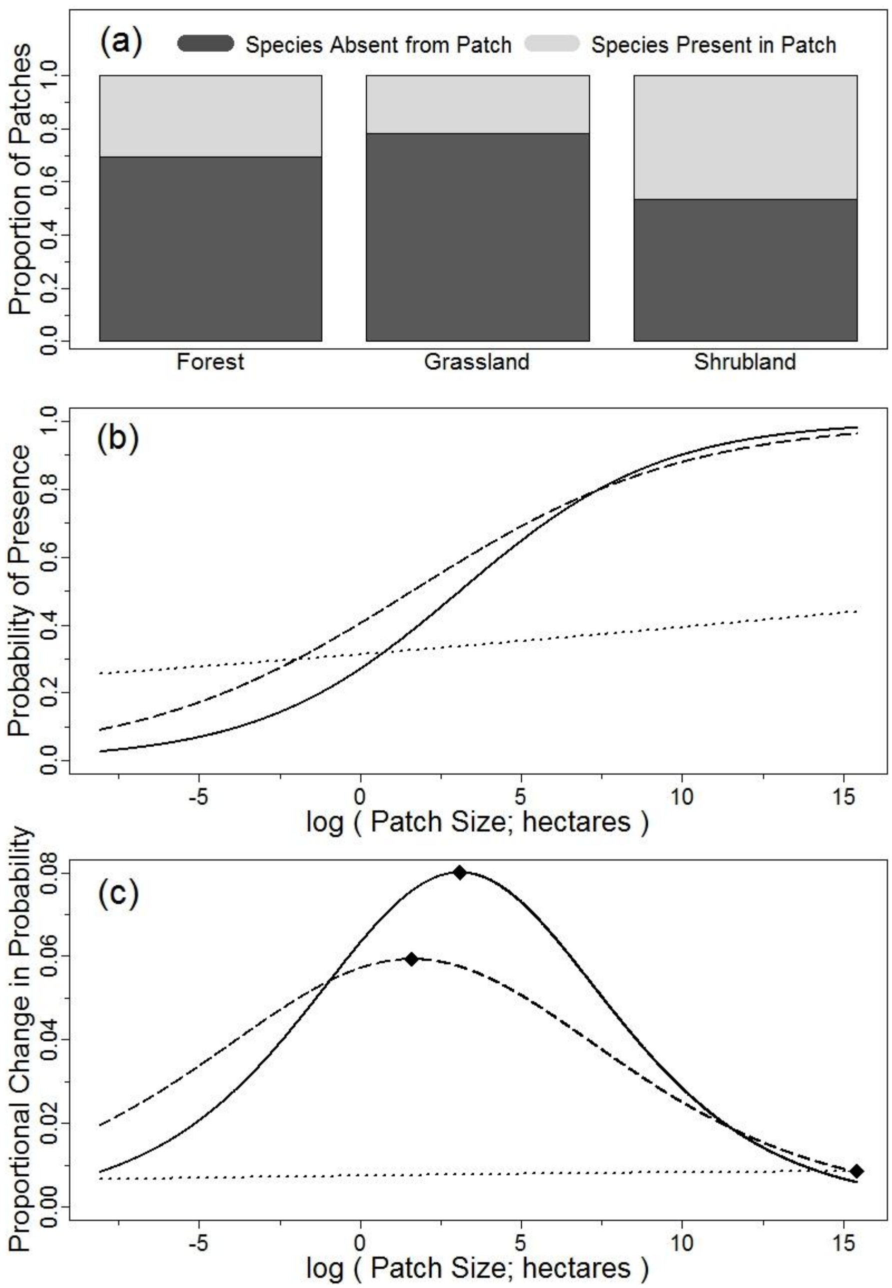

Figure 5 Relative impact of species and landscape characteristics on sensitivity (i.e., maximum proportional change in probability of presence; see Fig. 4c) graphed separately for each taxonomic class. Categories of habitat type are plotted on the lower axis. Relative values for the remaining variables are plotted on the upper axis, where low, medium and high signify 10th, 50th and 90th quantiles of continuous variables. Dashed lines are reference values generated for a habitat-generalist, omnivore in forested habitat using median values of all continuous variables.

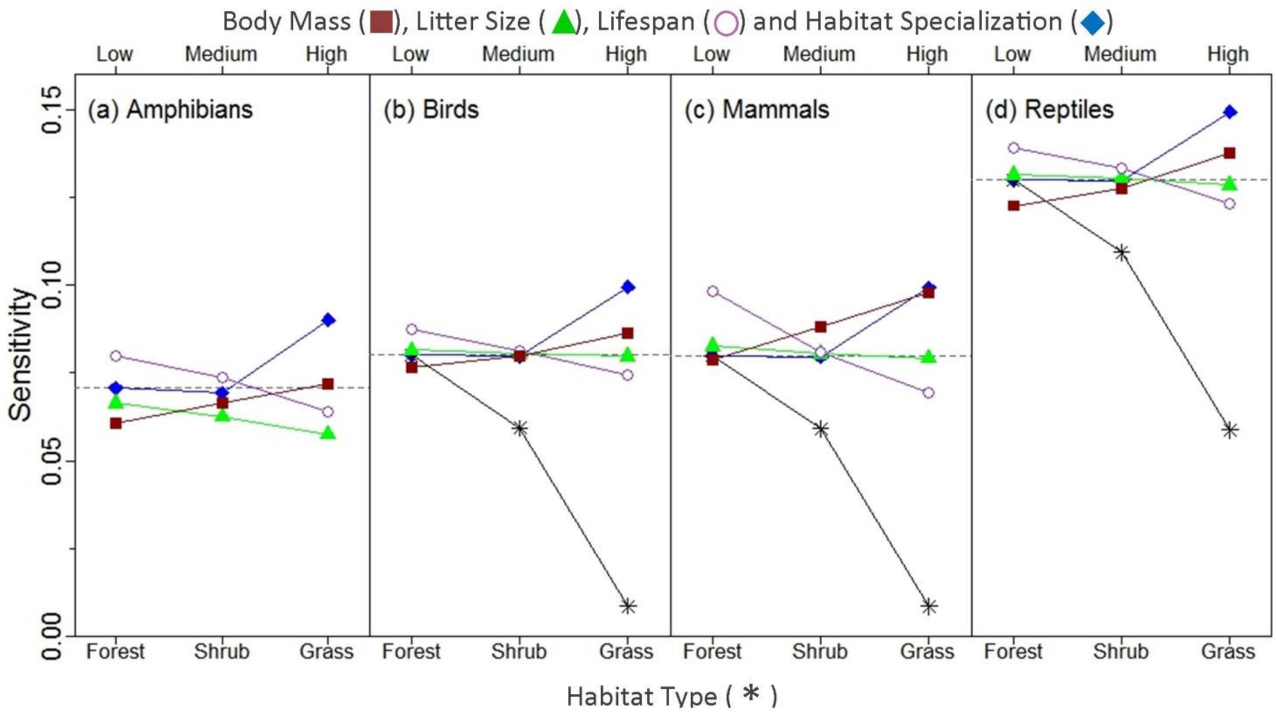

Figure 6. Probability of presence versus sensitivity for amphibians (cyan circles), birds (hollow circles), mammals (red squares), and reptiles (tan diamonds) analyzed in this study. Dashed lines are reference values for a habitat-generalist, omnivorous, forest bird using median values of all continuous variables. Marginal descriptions highlight species characteristics that pre-dispose animals to be in regions of the graph indicated by corresponding numbers on the plot. Photographs are of representative species from this study; clockwise from upper left: house mouse (*Mus musculus*), Costa's Hummingbird (*Calypte costae*), wood frog (*Lithobates sylvaticus*), southern brown bandicoot (*Isoodon obesulus*), Bearded Tree-quail (*Dendrortyx barbatus*), Abbott's duiker (*Cephalophus spadix*), and Barker's Anole (*Anolis barkeri*). See Acknowledgements for photo credits.

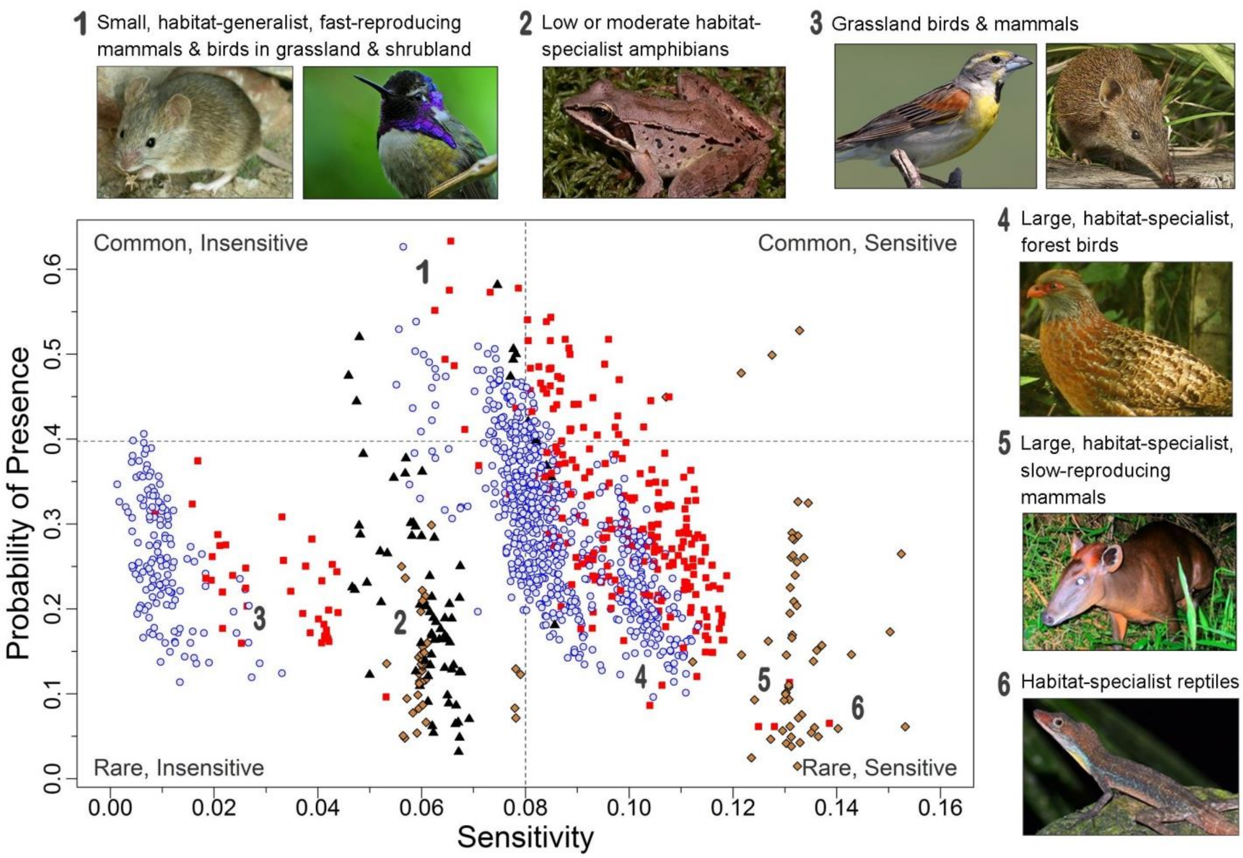

Table 1. List and brief description of landscape and species characteristics included in analyses.

Characteristic	Code	Category	Description
Patch Area	PLnPSize	Patch Metrics	Continuous variable representing the contiguous area of a remnant habitat patch, measured in hectares.
Habitat Type	LHSt	Landscape Metrics	Categorical variable indicating the major habitat type of patches included in a study. Categories are Forest, Grassland, and Shrubland.
Matrix Type	LMatrix	Landscape Metrics	Categorical variable representing the major driver of fragmentation for a study. Categories are Urban, Agriculture (e.g., crops, livestock), and Semi-natural (e.g., burn, flood).
Number of Patches	LPNum	Landscape Metrics	Ordinal variable indicating the number of habitat patches assessed within a study.
Landscape Size	LLnLandSize	Landscape Metrics	Continuous variable indicating the spatial extent of the landscape over which a study was conducted, measured in km2.
Landscape Impact	LLnLandImp	Landscape Metrics	Continuous variable representing the relative proportion of the landscape disturbed, calculated as the total area of patches divided by the landscape size.
Time Since Fragmentation	LLnFragTime	Landscape Metrics	Continuous variable representing the approximate time since habitat fragmentation, measured in years.
Latitude	LLatitude	Landscape Metrics	Continuous variable indicating the distance from the equator at which the study occurred, measured in degrees.
Litter Size	RLnLS	Species Trait	Continuous variable indicating the typical number of offspring per litter, measured as number of eggs or live-born young. (Typically referred to as clutch size for birds.)
Litters Per Year	RLnLPY	Species Trait	Ordinal variable indicating the typical number of litters per calendar year. (Typically referred to as clutches per year for birds.)
Age at First Reproduction	RLnAFR	Species Trait	Continuous variable indicating the typical age at which a species first produces offspring, measured in years.
Lifespan	RLnML	Species Trait	Continuous variable indicating the typical age of death for a species in the wild, measured in years.
Body Mass	SLnBM	Species Trait	Continuous variable indicating the typical adult body mass of a species, measure in grams.
Taxonomic Class	TC	Species Trait	Categorical variable indicating whether a species is an amphibian, bird, mammal, or reptile.
Primary Habitat	SHSt	Species Trait	Categorical variable representing habitat type with which a species is most commonly associated. Categories are Forest, Shrubland, Grassland, General, and Specific Feature (e.g., caves, cliffs, rock-outcrops).

Characteristic	Code	Category	Description
Habitat Specificity	SHSp	Species Trait	Categorical variable representing the degree of habitat specialization for a species. Categories are high specialization (only one primary habitat occupied), moderate specialization (two primary habitats occupied), or low specialization (more than two primary habitat types occupied).
Diet Class	SDC	Species Trait	Categorical variable representing the primary diet of a species. Categories are carnivore, herbivore, and omnivore.
Wetland Obligation	SW	Species Trait	Binary variable indicating whether or not a species is highly-dependent on wetland habitats (e.g., rivers, lakes, marshes, etc.).
Flight	SF	Species Trait	Binary variable indicating whether or not a species is capable of sustained flight.
Migratory Status	SM	Species Trait	Categorical variable representing whether species exhibits seasonal movements of long distances (> 200 km), short distances (20-200 km), or is essentially resident (< 20 km).
Range size	SLnSArea	Species Trait	Continuous variable indicating the geospatial extent of a species global range, measured in km2. For long-distance migrants, the smaller of breeding versus non-breeding range was used.

CHAPTER FOUR

Concluding remarks and application to Wyoming

Wyoming has a large list of Species of Greatest Conservation Need (SGCN), the distribution and actual conservation status of which are poorly understood due to large data gaps. These SGCN are faced with impending habitat conversion, particularly extraction of oil and natural gas and establishment of wind energy facilities. Given limited conservation funding, Wyoming wildlife managers therefore need to prioritize conservation of SGCN, which necessitates a quantitative estimate of their relative vulnerability. Vulnerability is the state of being susceptible to harm and, at its core, is primarily a function of exposure and susceptibility (Williams et al. 2008). In this dissertation, I have explored methods of quantitatively estimating both exposure and sensitivity.

I assessed modeled the distribution of Wyoming's SGCN (Chapter 1) and used those distributions in combination with projections of energy development activities to quantitatively estimate exposure (Chapter 2). Several species inhabiting Wyoming's basins had notably high exposure to development, with large increases expected in the near future (Fig. 1 of Chapter 2). Sixteen species had higher exposure than Greater Sage-grouse, which has experienced demonstrable population declines associated with energy development (Naugle et al. 2011a). Species with such large exposure values (e.g., Great Plains Toad, Pygmy Rabbit, and Wyoming Pocket Gopher) may be considered at potential risk of impact from energy development, and would therefore be logical targets of immediate conservation attention and/or research to quantify and mechanistically understand local impacts that could translate into population-level effects. This is particularly urgent if the same species are also sensitive to disturbance.

To assess species sensitivity to disturbance, I conducted a global meta-analysis of habitat disturbance studies to quantify species specific predictors of sensitivity (Chapter 3). Habitat specialization increased sensitivity to disturbance and interacted with class and habitat type. Although grassland species occurred in a lower proportion of patches, forest specialists and habitat-specific reptiles were particularly sensitive, and to a lesser degree fecundity, lifespan, and body mass also influenced sensitivity (e.g., Figs. 5, 6 of Chapter 3). I collected all these characteristics for Wyoming's SGCN (Table 1) and used the optimal model from Chapter 3 to predict their relative sensitivity (Table 2). Several species of reptiles (e.g., Black Hills Redbelly Snake, Midget Faded Rattlesnake, Rubber Boa, Greater Short-horned Lizard), as well as habitat specialist, and particularly larger, mammals (e.g., Moose, Abert's Squirrel) were identified as being sensitive.

Though how to explicitly weight exposure versus sensitivity is debatable, species that are both highly exposed to anthropogenic development of their habitat and have a high sensitivity to habitat fragmentation are likely to be at increased risk of experiencing population declines (e.g., labeled species in Fig. 1). If we put both exposure and sensitivity on the same scale, one way to calculate relative risk would be the simple arithmetic mean of the two (Table 2). Based on this metric, Wyoming pocket gopher is clearly the SGCN with the highest potential risk from energy development. Wyoming Pocket Gopher has an extremely narrow geographic range, with its entire global distribution restricted to portions of two counties in central Wyoming (Keinath et al. 2014). Within this area, it is further restricted to a narrow range of habitats, primarily saline basins characterized by Gardner's saltbush, to which it may be limited through competition with the much more common northern pocket gopher (*Thomomys talpoides*). Though demographics and population densities are largely unknown, it appears to occur in disjunct patches and very low densities across its range, and it is absent from many locations where it was previously known to occur. In combination with extensive oil and natural gas development across its limited range, these concerns led to a petition to list Wyoming pocket gopher under the U.S. Endangered Species Act, though it was denied listing due primarily a general lack of information on the species (USFWS 2010).

By the simple risk metric presented in Table 2, several other basin species also demonstrate high risk from energy development, particularly Greater Short-horned Lizard, Silky Pocket Mouse and Greater Sage-grouse and Black-tailed Prairie Dog. Sage Grouse is one of the few species that has undergone extensive research assessing impacts from energy development, and this has resulted in substantial evidence linking it to population declines (Naugle et al. 2011b). Additionally, Greater Sage-grouse is restricted to one habitat type; sagebrush. It can be found in a fairly broad structural range of sagebrush stands, but a specific combination of factors are necessary for successful breeding and recruitment, including the use of leks for mating, which are limited in the environment. In contrast to Greater Sage-grouse, Greater Short-horned lizard and Silky Pocket Mouse (and to a lesser extent Black-tailed Prairie Dog) have experienced virtually no conservation attention in Wyoming relative to energy development.

Abert's Squirrel is also at elevated risk, but Wyoming represents a very small portion of its range, which likely makes it a relatively low priority for conservation in the state. This situation brings up a profound question for wildlife managers. For all species identified as vulnerable in my analysis, further study and eventual conservation prioritization must consider the role of local populations in range wide persistence of the species in question (Lesica and Allendorf 1995). One could envision a third axis for Figure 1 that represents the species-specific context of Wyoming conservation. This may be as simple as the fraction of each species' global range (or ideally the fraction of its global population) that falls within Wyoming. Vulnerable species with a large proportion of their range in Wyoming (e.g., Greater Sage-grouse; >50% of range in Wyoming) could thus receive heightened attention, while species with very small portions of their range in Wyoming (e.g., Abert's Squirrel; <1% of range in Wyoming) could receive reduced attention. This approach would further solidify the Wyoming Pocket Gopher as a key priority for conservation attention, as 100% of its global range falls within Wyoming.

Although many other factors, such as cost, efficacy, and politics, must be considered when setting conservation priorities (Joseph et al. 2009), it is clear the vulnerability is an important part of the process. Herein I have provided a quantitative estimate of vulnerability that managers in Wyoming can use to inform decisions, and developed methods that can be applied to other species and areas.

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Figures and Tables

Figure 1. Wyoming's Species of Greatest Conservation Need plotted as a function of their relative exposure to energy development (Chapter 2; rescaled to range from 0 to 1) and their predicted sensitivity to habitat disturbance (Chapter 3; rescaled to range from 0 to 1). Species closer to the upper right corner of the graph have higher exposure and sensitivity, and are thus at relatively greater risk of being impacted by energy development. Reference lines are median values. Symbols represent amphibians (black triangles), birds (hollow circles), mammals (red squares), and reptiles (tan diamonds). Some of the most at risk species are identified. Values used to create this graph are presented in Table 1.

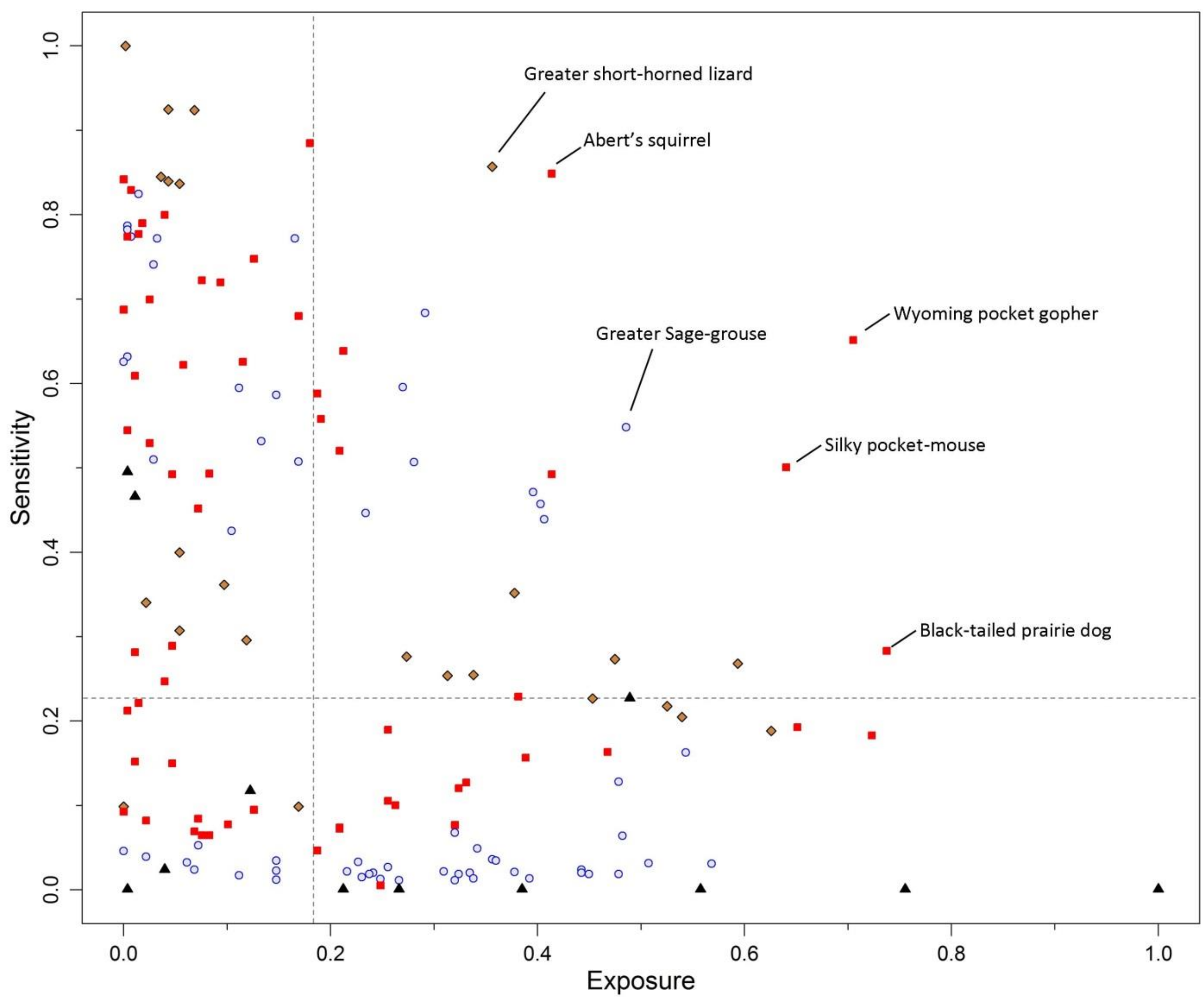


Table 1. Life history characteristics used to predict species sensitivity for all Wyoming's Species of Greatest Conservation Need. Characteristics are explained in Table 1 of Chapter 3.

Class	Species Code	Habitat Specificity	Primary Habitat	Diet Class	Body Mass (g)	Litters per Year	Litter Size	Lifespan (y)
Amphibian	AMBU	3	General	Carn	120	1.0	15000	9.0
Amphibian	BCFR	3	General	Carn	2	1.0	160	3.0
Amphibian	BOTO	1	Grass	Carn	38	1.0	5200	10.2
Amphibian	CSFR	3	Forest	Carn	28	1.0	600	9.0
Amphibian	GBSP	3	Shrub	Carn	11	1.0	663	16.0
Amphibian	GPTO	2	Grass	Carn	86	2.0	11037	12.8
Amphibian	NLFR	3	General	Carn	17	1.0	4073	9.0
Amphibian	RMTO	3	General	Carn	86	1.0	20000	15.0
Amphibian	SLSP	2	Grass	Carn	30	1.0	2000	13.0
Amphibian	TISA	3	Grass	Carn	13	1.0	3500	16.0
Amphibian	WOFR	3	Forest	Carn	10	1.0	815	4.8
Amphibian	WYTO	1	Grass	Carn	14	1.0	3500	2.0
Bird	AMBI	2	General	Carn	540	1.0	4	8.2
Bird	ATFC	3	Forest	Carn	28	1.5	4	10.5
Bird	ATTW	1	Forest	Carn	57	1.0	5	7.6
Bird	AWPE	3	General	Carn	6078	1.0	2	35.6
Bird	BAGO	3	General	Herb	981	1.0	10	17.5
Bird	BBWP	1	Forest	Carn	70	1.0	4	8.0
Bird	BCNH	3	General	Carn	800	1.0	4	21.1
Bird	BCRF	3	Grass	Herb	26	1.0	5	6.0
Bird	BESU	3	General	Carn	4544	1.0	2	35.4
Bird	BEWI	3	General	Carn	4544	1.0	2	35.4
Bird	BLTE	3	General	Carn	59	1.0	3	18.0
Bird	BOBO	3	Grass	Herb	34	1.2	5	8.3
Bird	BOOW	1	Forest	Carn	136	1.0	5	10.6
Bird	BRFI	3	Grass	Herb	25	1.0	5	7.0
Bird	BRSP	2	Shrub	Gen	11	1.0	3	5.9
Bird	BUOW	3	Grass	Carn	162	1.2	8	9.2
Bird	BUSH	3	General	Carn	5	2.0	6	8.7
Bird	CABA	2	Grass	Herb	1211	1.0	9	25.9
Bird	CATE	3	Misc	Carn	605	1.0	2	30.0
Bird	CCLS	1	Grass	Gen	20	2.0	5	4.3
Bird	CLGR	3	Misc	Carn	1114	1.0	3	12.5
Bird	COLO	2	Misc	Carn	4380	1.0	2	18.5
Bird	CSTG	3	Shrub	Gen	870	1.0	12	7.2
Bird	DICK	3	Grass	Gen	28	1.0	4	4.5
Bird	FEHA	3	Grass	Carn	1508	1.0	3	22.6
Bird	FOTE	3	Misc	Carn	149	1.0	3	15.9
Bird	FRGU	3	General	Carn	265	1.0	3	9.5
Bird	GBHE	3	General	Carn	2460	1.5	4	23.8
Bird	GGOW	3	Forest	Carn	1118	1.0	4	17.5
Bird	GRSP	3	Grass	Gen	18	2.0	4	7.9
Bird	GSGR	2	Shrub	Gen	2207	1.0	7	8.0
Bird	GSHC	3	General	Herb	3987	1.0	2	30.0

Class	Species Code	Habitat Specificity	Primary Habitat	Diet Class	Body Mass (g)	Litters per Year	Litter Size	Lifespan (y)
Bird	HADU	2	Forest	Carn	570	1.0	6	14.7
Bird	JUTI	3	Forest	Herb	17	1.0	7	8.7
Bird	LABU	3	Grass	Gen	37	1.0	5	4.7
Bird	LBCU	3	Grass	Carn	644	1.0	4	24.0
Bird	LESC	3	General	Herb	796	1.0	10	18.2
Bird	LEWO	1	Forest	Carn	107	1.0	7	9.6
Bird	MCLO	2	Grass	Gen	25	2.0	3	5.0
Bird	MERL	3	General	Carn	186	1.0	5	12.5
Bird	MOPL	1	Grass	Carn	99	2.5	4	8.6
Bird	NOGO	1	Forest	Carn	1012	1.2	3	19.1
Bird	NPOW	1	Forest	Carn	65	1.0	4	5.0
Bird	PEFA	3	General	Carn	944	1.3	3	20.6
Bird	PYNU	1	Forest	Herb	11	1.3	7	7.6
Bird	REHE	2	General	Herb	1064	1.0	10	21.8
Bird	SASP	3	Shrub	Gen	18	2.0	3	8.0
Bird	SATH	2	Shrub	Herb	43	1.5	4	11.6
Bird	SCOR	3	General	Herb	36	1.0	3	6.3
Bird	SEOW	3	Grass	Carn	360	1.5	7	15.1
Bird	SNEG	3	General	Carn	360	1.0	4	20.2
Bird	SWHA	3	General	Carn	974	1.0	3	22.2
Bird	TRSW	3	General	Herb	11357	1.0	6	25.8
Bird	UPSA	3	Grass	Carn	153	1.0	4	8.9
Bird	VIRA	3	General	Herb	84	1.5	9	8.2
Bird	WEGR	3	Misc	Carn	1279	1.0	3	13.2
Bird	WESJ	3	Forest	Herb	84	1.0	4	15.6
Bird	WFIB	2	General	Carn	593	1.0	3	15.3
Bird	WIFC	3	General	Carn	13	1.0	4	11.0
Bird	YBCC	3	Forest	Carn	67	1.0	4	4.8
Mammal	ABSQ	1	Forest	Gen	706	1.4	3	7.0
Mammal	AMPI	1	Grass	Gen	137	2.1	3	7.0
Mammal	BBBA	1	General	Carn	21	1.0	2	19.3
Mammal	BFFE	1	Grass	Carn	854	1.0	3	11.1
Mammal	BISH	1	General	Gen	70313	1.0	1	21.1
Mammal	BMJM	2	Grass	Gen	18	2.0	5	5.1
Mammal	BTPD	1	Grass	Gen	1106	1.0	4	8.8
Mammal	CALY	1	Forest	Carn	9671	1.0	3	26.8
Mammal	CAMO	3	Shrub	Herb	19	2.0	3	5.3
Mammal	CLCH	3	Shrub	Gen	85	2.0	3	12.6
Mammal	DWSH	2	Grass	Carn	3	2.0	6	1.3
Mammal	ERBA	1	Forest	Carn	14	1.0	3	19.2
Mammal	FISH	1	Forest	Carn	3031	1.0	3	11.1
Mammal	FRBA	1	Shrub	Carn	8	1.0	1	18.3
Mammal	GBPM	2	Shrub	Gen	24	2.2	5	5.2
Mammal	GRBE	1	Forest	Herb	219947	0.3	2	39.9
Mammal	HASH	3	Grass	Herb	4	3.0	6	2.0
Mammal	HOBA	1	Forest	Carn	29	1.0	2	6.0
Mammal	HPMO	2	Grass	Gen	42	2.0	6	2.0

Class	Species Code	Habitat Specificity	Primary Habitat	Diet Class	Body Mass (g)	Litters per Year	Litter Size	Lifespan (y)
Mammal	IPGO	2	Grass	Gen	80	4.0	1	1.0
Mammal	LBBA	1	General	Carn	11	1.0	1	25.0
Mammal	LEBA	1	Forest	Carn	7	1.0	1	12.1
Mammal	LEWE	1	General	Carn	53	1.4	5	9.8
Mammal	LLBA	1	Forest	Carn	9	1.0	1	9.1
Mammal	MART	1	Forest	Carn	841	1.0	3	17.8
Mammal	MOOS	1	Forest	Herb	423950	1.0	1	27.0
Mammal	NFSQ	2	Forest	Herb	122	1.0	3	13.2
Mammal	NOBA	1	Forest	Carn	9	1.0	1	18.5
Mammal	OBPM	2	Grass	Gen	11	1.5	5	1.0
Mammal	PABA	1	Shrub	Carn	24	1.0	2	11.0
Mammal	PIMO	3	Shrub	Gen	28	3.7	3	3.2
Mammal	PLHM	2	Grass	Herb	10	2.0	4	3.8
Mammal	PMJM	2	Grass	Gen	18	2.0	5	5.1
Mammal	PPGO	2	Grass	Gen	277	1.0	3	8.7
Mammal	PPMO	2	Shrub	Gen	10	2.5	4	2.0
Mammal	PRSH	1	General	Carn	3	2.0	2	3.0
Mammal	PRVO	1	Grass	Gen	41	4.0	4	3.8
Mammal	PYRA	2	Grass	Gen	438	2.5	6	2.0
Mammal	PYSH	1	General	Gen	4	1.0	4	2.0
Mammal	RING	1	Shrub	Herb	994	1.0	3	16.9
Mammal	RIOT	1	Misc	Carn	7384	0.9	3	24.4
Mammal	SBVO	2	Grass	Gen	33	3.0	5	4.3
Mammal	SFBA	3	Grass	Carn	5	1.0	1	12.0
Mammal	SGSQ	2	Shrub	Herb	144	2.0	6	7.9
Mammal	SHBA	1	Forest	Carn	12	1.0	2	12.0
Mammal	SPBA	1	Forest	Carn	18	1.0	1	19.2
Mammal	SPMO	2	Shrub	Gen	8	2.0	4	3.8
Mammal	SWFO	1	Grass	Carn	2505	1.0	4	19.0
Mammal	TBEB	1	Grass	Carn	12	1.0	1	13.6
Mammal	UGSQ	2	Grass	Herb	366	1.0	5	5.0
Mammal	UNCH	2	Forest	Gen	85	1.0	4	10.0
Mammal	VASH	3	General	Carn	6	2.2	5	1.8
Mammal	WASH	1	General	Carn	13	2.6	6	1.5
Mammal	WAVO	2	Forest	Gen	63	3.0	5	1.5
Mammal	WGSQ	2	Grass	Gen	324	1.0	6	7.9
Mammal	WHVO	2	Grass	Gen	30	2.4	5	4.0
Mammal	WOLV	1	General	Carn	17992	0.5	3	15.8
Mammal	WPGO	2	Shrub	Gen	45	4.0	4	1.0
Mammal	WTPD	2	Grass	Gen	1332	1.0	5	8.0
Mammal	YPCH	3	Shrub	Gen	73	1.0	5	5.0
Reptile	BHRS	3	Forest	Carn	8	1.0	8	5.0
Reptile	BULL	3	General	Carn	1149	1.0	11	33.0
Reptile	EYBR	3	General	Carn	209	1.0	15	10.0
Reptile	GBGS	3	General	Carn	2073	1.0	11	33.0
Reptile	GPEL	3	General	Carn	6	1.0	5	4.0
Reptile	GSHO	2	Shrub	Carn	18	1.0	10	5.0

Class	Species Code	Habitat Specificity	Primary Habitat	Diet Class	Body Mass (g)	Litters per Year	Litter Size	Lifespan (y)
Reptile	MFRS	1	Shrub	Carn	70	1.0	5	20.0
Reptile	NMLS	2	Grass	Carn	13	1.0	5	6.0
Reptile	NSBL	3	General	Carn	5	2.0	6	6.0
Reptile	NTLI	3	Shrub	Carn	5	3.0	7	5.0
Reptile	PAMS	3	General	Carn	194	1.0	10	22.8
Reptile	PFLI	3	General	Carn	7	2.0	7	4.0
Reptile	PHNS	3	Grass	Carn	200	0.5	12	19.9
Reptile	PLGA	3	Grass	Carn	66	1.0	15	8.7
Reptile	PRLI	2	Misc	Carn	7	2.0	8	5.0
Reptile	PRRR	2	Shrub	Carn	12	2.0	4	6.0
Reptile	PRRS	3	General	Carn	631	0.5	10	27.1
Reptile	RSGS	3	General	Carn	150	1.0	27	15.0
Reptile	RUBO	2	Forest	Carn	163	0.5	4	28.2
Reptile	SGSN	3	Grass	Carn	46	1.0	8	6.0
Reptile	VAGS	3	General	Carn	150	1.0	27	15.0
Reptile	WAGS	3	General	Carn	200	1.0	9	23.0
Reptile	WPTU	3	General	Herb	400	3.0	12	60.0
Reptile	WSSS	3	General	Carn	1500	2.0	18	25.1

Table 2. Scaled exposure and sensitivity values (Fig. 1) for all Wyoming's Species of Greatest Conservation Need. Species are ordered by decreasing risk, which is simply the arithmetic mean of the exposure and sensitivity values. Species falling in the upper right quadrant of Figure 1 (i.e., having both exposure and sensitivity values greater than their respective medians) are flagged with "Yes" in the Above Median column.

Species	Species Code	Class	Exposure	Sensitivity	Risk	Above Median
Wyoming Pocket Gopher	WPGO	Mammal	0.71	0.65	0.68	Yes
Abert's Squirrel	ABSQ	Mammal	0.41	0.85	0.63	Yes
Greater Short-horned Lizard	GSHO	Reptile	0.36	0.86	0.61	Yes
Silky Pocket Mouse	SPMO	Mammal	0.64	0.50	0.57	Yes
Moose	MOOS	Mammal	0.18	0.88	0.53	-
Greater Sage-Grouse	GSGR	Bird	0.48	0.55	0.52	Yes
Black-tailed Prairie Dog	BTPD	Mammal	0.74	0.28	0.51	Yes
Black Hills Redbelly Snake	BHRS	Reptile	0.00	1.00	0.5	-
Great Plains Toad	GPTO	Amphibian	1.00	0.00	0.5	-
Midget Faded Rattlesnake	MFRS	Reptile	0.07	0.92	0.5	-
Yellow-billed Cuckoo	YBCC	Bird	0.29	0.68	0.49	Yes
Rubber Boa	RUBO	Reptile	0.04	0.92	0.48	-
Lewis' Woodpecker	LEWO	Bird	0.16	0.77	0.47	-
Pygmy Rabbit	PYRA	Mammal	0.72	0.18	0.45	-
Great Basin Pocket Mouse	GBPM	Mammal	0.41	0.49	0.45	Yes
Northern Tree Lizard	NTLI	Reptile	0.05	0.84	0.44	-
Prairie Lizard	PRLI	Reptile	0.04	0.84	0.44	-
Prairie Racerunner	PRRR	Reptile	0.04	0.85	0.44	-
Long-legged Myotis	LLBA	Mammal	0.13	0.75	0.44	-
Brewer's Sparrow	BRSP	Bird	0.40	0.47	0.43	Yes
Ash-throated Flycatcher	ATFC	Bird	0.27	0.60	0.43	Yes
Sage Sparrow	SASP	Bird	0.40	0.46	0.43	Yes
Western Painted Turtle	WPTU	Reptile	0.59	0.27	0.43	Yes
River Otter	RIOT	Mammal	0.21	0.64	0.42	Yes
Eastern Red Bat	ERBA	Mammal	0.17	0.68	0.42	-
Sage Thrasher	SATH	Bird	0.41	0.44	0.42	Yes
Fisher	FISH	Mammal	0.00	0.84	0.42	-
Black-footed Ferret	BFFE	Mammal	0.65	0.19	0.42	-
Hoary Bat	HOBA	Mammal	0.04	0.80	0.42	-
Northern Pygmy-Owl	NPOW	Bird	0.01	0.82	0.42	-
Grizzly Bear	GRBE	Mammal	0.01	0.83	0.42	-
Plains Gartersnake	PLGA	Reptile	0.63	0.19	0.41	-
Long-eared Myotis	LEBA	Mammal	0.09	0.72	0.41	-
Canada Lynx	CALY	Mammal	0.02	0.79	0.4	-
Northern Goshawk	NOGO	Bird	0.03	0.77	0.4	-
Silver-haired Bat	SHBA	Mammal	0.08	0.72	0.4	-
Water Vole	WAVO	Mammal	0.01	0.78	0.4	-
Black-backed Woodpecker	BBWP	Bird	0.00	0.79	0.39	-
Western Grebe	WEGR	Bird	0.28	0.51	0.39	Yes
American Three-toed Woodpecker	ATTW	Bird	0.00	0.78	0.39	-

Species	Species Code	Class	Exposure	Sensitivity	Risk	Above Median
Boreal Owl	BOOW	Bird	0.01	0.77	0.39	-
Marten	MART	Mammal	0.00	0.77	0.39	-
Pallid Bat	PABA	Mammal	0.19	0.59	0.39	Yes
Pygmy Nuthatch	PYNU	Bird	0.03	0.74	0.38	-
Rocky Mountain Toad	RMTO	Amphibian	0.76	0.00	0.38	-
Plains Pocket Mouse	PPMO	Mammal	0.19	0.56	0.37	Yes
Bullsnake	BULL	Reptile	0.47	0.27	0.37	Yes
Plains Hog-nosed Snake	PHNS	Reptile	0.54	0.21	0.37	-
Eastern Yellow-bellied Racer	EYBR	Reptile	0.53	0.22	0.37	-
Ringtail	RING	Mammal	0.11	0.63	0.37	-
Western Scrub-Jay	WESJ	Bird	0.15	0.59	0.37	-
Northern Sagebrush Lizard	NSBL	Reptile	0.38	0.35	0.37	Yes
Yellow-pine Chipmunk	YPCH	Mammal	0.21	0.52	0.36	Yes
Spotted Bat	SPBA	Mammal	0.02	0.70	0.36	-
Great Basin Spadefoot	GBSP	Amphibian	0.49	0.23	0.36	Yes
Chestnut-collared Longspur	CCLS	Bird	0.54	0.16	0.35	-
Juniper Titmouse	JUTI	Bird	0.11	0.59	0.35	-
Northern Myotis	NOBA	Mammal	0.00	0.69	0.34	-
Western Spiny Softshell	WSSS	Reptile	0.45	0.23	0.34	Yes
Forster's Tern	FOTE	Bird	0.23	0.45	0.34	Yes
Unita Chipmunk	UNCH	Mammal	0.06	0.62	0.34	-
Clark's Grebe	CLGR	Bird	0.17	0.51	0.34	-
Columbian Sharp-tailed Grouse	CSTG	Bird	0.13	0.53	0.33	-
Great Gray Owl	GGOW	Bird	0.00	0.63	0.32	-
Least Weasel	LEWE	Mammal	0.47	0.16	0.31	-
Harlequin Duck	HADU	Bird	0.00	0.63	0.31	-
Northern Flying Squirrel	NFSQ	Mammal	0.01	0.61	0.31	-
Prairie Vole	PRVO	Mammal	0.38	0.23	0.3	Yes
Mountain Plover	MOPL	Bird	0.48	0.13	0.3	-
Upland Sandpiper	UPSA	Bird	0.57	0.03	0.3	-
Prairie Rattlesnake	PRRS	Reptile	0.34	0.25	0.3	Yes
Canyon Mouse	CAMO	Mammal	0.08	0.49	0.29	-
Pale Milksnake	PAMS	Reptile	0.31	0.25	0.28	Yes
Plains Spadefoot	SLSP	Amphibian	0.56	0.00	0.28	-
Fringed Myotis	FRBA	Mammal	0.02	0.53	0.28	-
Wandering Gartersnake	WAGS	Reptile	0.27	0.28	0.28	Yes
Pinyon Mouse	PIMO	Mammal	0.01	0.54	0.27	-
Lark Bunting	LABU	Bird	0.48	0.06	0.27	-
Olive-backed Pocket Mouse	OBPM	Mammal	0.39	0.16	0.27	-
Spotted Ground Squirrel	SGSQ	Mammal	0.05	0.49	0.27	-
Common Loon	COLO	Bird	0.03	0.51	0.27	-
Grasshopper Sparrow	GRSP	Bird	0.51	0.03	0.27	-
Caspian Tern	CATE	Bird	0.10	0.43	0.26	-
Cliff Chipmunk	CLCH	Mammal	0.07	0.45	0.26	-
Wood Frog	WOFR	Amphibian	0.00	0.50	0.25	-
Short-eared Owl	SEOW	Bird	0.48	0.02	0.25	-
Columbia Spotted Frog	CSFR	Amphibian	0.01	0.47	0.24	-

Species	Species Code	Class	Exposure	Sensitivity	Risk	Above Median
Bald Eagle (winter)	BEWI	Bird	0.45	0.02	0.23	-
Burrowing Owl	BUOW	Bird	0.44	0.02	0.23	-
Ferruginous Hawk	FEHA	Bird	0.44	0.02	0.23	-
Plateau Fence Lizard	PFLI	Reptile	0.10	0.36	0.23	-
White-tailed Prairie Dog	WTPD	Mammal	0.33	0.13	0.23	-
Great Plains Earless Lizard	GPEL	Reptile	0.05	0.40	0.23	-
Uinta Ground Squirrel	UGSQ	Mammal	0.32	0.12	0.22	-
Swift Fox	SWFO	Mammal	0.25	0.19	0.22	-
Great Basin Gophersnake	GBGS	Reptile	0.12	0.30	0.21	-
Long-billed Curlew	LBCU	Bird	0.39	0.01	0.2	-
Great Blue Heron	GBHE	Bird	0.38	0.02	0.2	-
Sagebrush Vole	SBVO	Mammal	0.32	0.08	0.2	-
Bobolink	BOBO	Bird	0.36	0.03	0.2	-
Virginia Rail	VIRA	Bird	0.36	0.04	0.2	-
McCown's Longspur	MCLO	Bird	0.34	0.05	0.19	-
Dickcissel	DICK	Bird	0.32	0.07	0.19	-
Boreal Chorus Frog	BCFR	Amphibian	0.38	0.00	0.19	-
Wyoming Ground Squirrel	WGSQ	Mammal	0.26	0.10	0.18	-
Smooth Green Snake	SGSN	Reptile	0.02	0.34	0.18	-
Idaho Pocket Gopher	IPGO	Mammal	0.25	0.11	0.18	-
Northern Many-lined Skink	NMLS	Reptile	0.05	0.31	0.18	-
Swainson's Hawk	SWHA	Bird	0.34	0.02	0.18	-
Redhead	REHE	Bird	0.34	0.01	0.18	-
White-faced Ibis	WFIB	Bird	0.32	0.02	0.17	-
Water Shrew	WASH	Mammal	0.05	0.29	0.17	-
Black Tern	BLTE	Bird	0.32	0.01	0.17	-
Merlin	MERL	Bird	0.31	0.02	0.16	-
Bighorn Sheep	BISH	Mammal	0.01	0.28	0.15	-
Pygmy Shrew	PYSH	Mammal	0.04	0.25	0.14	-
Plains Harvest Mouse	PLHM	Mammal	0.21	0.07	0.14	-
American Bittern	AMBI	Bird	0.26	0.03	0.14	-
Big Brown Bat	BBBA	Mammal	0.21	0.07	0.14	-
Canvasback	CABA	Bird	0.27	0.01	0.14	-
Red-sided Gartersnake	RSGS	Reptile	0.17	0.10	0.13	-
Northern Leopard Frog	NLFR	Amphibian	0.27	0.00	0.13	-
American White Pelican	AWPE	Bird	0.24	0.02	0.13	-
Willow Flycatcher	WIFC	Bird	0.25	0.01	0.13	-
Greater Sandhill Crane	GSHC	Bird	0.23	0.03	0.13	-
Bald Eagle (summer)	BESU	Bird	0.24	0.02	0.13	-
Western Small-footed Myotis	SFBA	Mammal	0.25	0.00	0.13	-
Snowy Egret	SNEG	Bird	0.23	0.02	0.12	-
Wyoming Toad	WYTO	Amphibian	0.12	0.12	0.12	-
Lesser Scaup	LESC	Bird	0.21	0.02	0.12	-
American Pika	AMPI	Mammal	0.01	0.22	0.12	-
Little Brown Myotis	LBBA	Mammal	0.19	0.05	0.12	-
Dwarf Shrew	DWSH	Mammal	0.12	0.10	0.11	-
Wolverine	WOLV	Mammal	0.00	0.21	0.11	-

Species	Species Code	Class	Exposure	Sensitivity	Risk	Above Median
Tiger Salamander	TISA	Amphibian	0.21	0.00	0.11	-
Hispid Pocket Mouse	HPMO	Mammal	0.05	0.15	0.1	-
Franklin's Gull	FRGU	Bird	0.15	0.03	0.09	-
Vagrant Shrew	VASH	Mammal	0.10	0.08	0.09	-
Peregrine Falcon	PEFA	Bird	0.15	0.02	0.08	-
Preble's Shrew	PRSH	Mammal	0.01	0.15	0.08	-
Bushtit	BUSH	Bird	0.15	0.01	0.08	-
Plains Pocket Gopher	PPGO	Mammal	0.07	0.08	0.08	-
Bear Lodge Meadow Jumping Mouse	BMJM	Mammal	0.08	0.06	0.07	-
Preble's Meadow Jumping Mouse	PMJM	Mammal	0.07	0.06	0.07	-
Townsend's Big-eared Bat	TBEB	Mammal	0.07	0.07	0.07	-
Black-crowned Night-Heron	BCNH	Bird	0.11	0.02	0.06	-
Scott's Oriole	SCOR	Bird	0.07	0.05	0.06	-
Western Heather Vole	WHVO	Mammal	0.02	0.08	0.05	-
Valley Gartersnake	VAGS	Reptile	0.00	0.10	0.05	-
Hayden's Shrew	HASH	Mammal	0.00	0.09	0.05	-
Trumpeter Swan	TRSW	Bird	0.06	0.03	0.05	-
Barrow's Goldeneye	BAGO	Bird	0.07	0.02	0.05	-
Boreal Toad	BOTO	Amphibian	0.04	0.02	0.03	-
Black Rosy-Finch	BRFI	Bird	0.02	0.04	0.03	-
Brown-capped Rosy Finch	BCRF	Bird	0.00	0.05	0.02	-
American Bullfrog	AMBU	Amphibian	0.00	0.00	0	-

APPENDICES

Appendix A: Tables of predictor layers and detailed distribution model statistics

Table A1. Predictor layers used in distribution models, with notes on units and scale.

Predictor Layer	Units	Notes on Units and Scale
Elevation	Meters	Elevation above sea level
Degree Slope	Degrees	Ranges from 0 (flat) to 90 (vertical)
8-Category Aspect	Categorical	-1 (Flat); 0 (North); 1 (Northeast); 2 (East); 3 (Southeast); 4 (South); 5 (Southwest); 6 (West); 7 (Northwest)
A^1 (Transformed Aspect)	Unitless	Ranges from 0 (southwest aspect) to 2 (northeast aspect)
Radiation Load	Unitless	Ranges from near 0 (flat southwest aspect) upward toward 180 (steepest northeast aspect)
Vector Ruggedness Measure	Unitless	Ranges from 0 (flat) to 1 (most rugged)
Compound Topographic Index	Unitless	Lower values represent drier areas, higher values represent wetter areas
Landform Classification	Categorical	1 (Canyons, incised streams); 2 (Midslope drainages, shallow valleys); 3 (Upland drainages, headwaters); 4 (U-shape valleys); 5 (Plains); 6 (Open Slopes); 7 (Upper slopes, mesas); 8 (Local ridges, hills in valleys); 9 (Midslope ridges, small hills in plains); 10 (Mountain tops, high ridges)
Potential for Rock Outcrop	Meters	Distance to potential rock outcrops
Distance to cliffs	Meters	Distance to areas of steep slope
Contagion Index	Unitless	Low values represent areas with high patch interspersion, higher values represent landscapes with fewer, larger patches.
Distance to primary & secondary roads	Meters	
Human Footprint	Meters	Distance to developed areas
Vegetation Indices (includes forest cover, ponderosa pine, pinion-juniper, herbaceous, sagebrush, shrub cover, cottonwood, conifer, and deciduous forest)	Unitless	Higher values indicate greater potential prevalence of the specified vegetation type. Ranges from 0 (specified vegetation does not occur within 800 meters) to 1 (all area within 800 meters is likely to contain the specified vegetation).
Sagebrush	Percent	Percent cover of sagebrush
Percent Forest Cover	Percent	Percent cover of trees
Distance to permanent snow	Meters	
Bare Ground index	Unitless	Higher values indicate greater potential for prevalence of bare ground. Ranges from 0

Predictor Layer	Units	Notes on Units and Scale
		(no bare ground) to 1 (entirely bare ground).
Predictor Layer	Units	Notes on Units and Scale
Depth to Shallowest Restrictive Layer	Centimeters	Distance from soil surface to bedrock.
Soil texture	Categorical	Ordinal variable ranging from 0 (finest) to 5 (coarsest).
Soil - Fraction Sand	Percent	
Soil - Fraction Clay	Percent	
Distance to cave-forming formations	Meters	
Distance to Water (several layers based on different features)	Meters	
Prevalence of water features within neighborhood (several layers based on different features and neighborhood sizes)	Unitless	Corresponds to the percentage of pixels in a defined neighborhood that contain the selected water features. Range from 0 (no pixels contain water features) to 1 (100% of pixels contain water features)
Precipitation (includes mean annual precipitation, precipitation of the wettest month, precipitation of the driest month, annual precipitation range, precipitation of the wettest quarter, precipitation of the driest quarter, precipitation of the warmest quarter, precipitation of the coldest quarter, and variation of monthly precipitation)	0.1 cm	Values are presented in tenths of centimeters, representing depth of water.
Humidity (includes annual mean relative humidity, relative humidity of the most humid month, relative humidity of the least humid month, annual relative humidity range, and variation of monthly Relative Humidity)	0.10%	Values are presented in hundredth-percentages of relative humidity.
Radiation (includes annual total radiation, radiation of the lightest month, radiation of the darkest month, annual radiation range, and variation of monthly radiation)	0.01 $MJ/m^2/day$	Values are presented in hundredths of millijoules per meter square of surface per day.
Temperature (includes annual mean temperature, mean diurnal range, hottest month mean maximum temperature, coldest month mean minimum temperature, annual temperature range, isothermality, standard deviation of monthly temperature, wettest quarter mean temperature, driest quarter mean temperature, warmest quarter mean temperature, and coldest quarter mean temperature)	0.1 °C	Values are presented in tenths of a degree Celsius.
Annual number of Frost-free Days	0.1 Days	Values are presented in tenths of days.
Interannual variation in annual number of frost days	0.1 Days	Values are presented in tenths of days.

Predictor Layer	Units	Notes on Units and Scale
Black-Tailed/White-Tailed Prairie Dog Combined Models	Unitless	Ranges from 0 (lowest probability of Prairie Dog occurrence) to 1 (highest probability of Prairie Dog occurrence)
Public land	Categorical	0 = Private; 1 = Public

Table A2. Species Codes for Wyoming Species of Greatest Conservation Need for which distribution models were created.

Taxonomic Class	Species Code	Species
Amphibian	AMBU	American Bullfrog (Lithobates catesbieanus)
Amphibian	BCFR	Boreal Chorus Frog (Pseudacris maculata)
Amphibian	BOTO	Boreal Toad (Anaxyrus boreas boreas)
Amphibian	CSFR	Columbia Spotted Frog (Rana luteiventris)
Amphibian	GBSP	Great Basin Spadefoot (Spea intermontana)
Amphibian	GPTO	Great Plains Toad (Anaxyrus cognatus)
Amphibian	NLFR	Northern Leopard Frog (Lithobates pipiens)
Amphibian	RMTO	Rocky Mountain Toad (Anaxyrus woodhousii woodhousii)
Amphibian	SLSP	Plains Spadefoot (Spea bombifrons)
Amphibian	TISA	Tiger Salamander (Ambystoma mavortium)
Amphibian	WOFR	Wood Frog (Lithobates sylvaticus)
Amphibian	WYTO	Wyoming Toad (Anaxyrus baxteri)
Bird	AMBI	American Bittern (Botaurus lentiginosus)
Bird	ATFC	Ash-throated Flycatcher (Myiarchus cinerascens)
Bird	ATTW	American Three-toed Woodpecker (Picoides dorsalis)
Bird	AWPE	American White Pelican (Pelecanus erythrorhynchos)
Bird	BAGO	Barrow's Goldeneye (Bucephala islandica)
Bird	BBWP	Black-backed Woodpecker (Picoides arcticus)
Bird	BCNH	Black-crowned Night-Heron (Nycticorax nycticorax)
Bird	BCRF	Brown-capped Rosy Finch (Leucosticte australis)
Bird	BESU	Bald Eagle (summer) (Haliaeetus leucocephalus (summer))
Bird	BEWI	Bald Eagle (winter) (Haliaeetus leucocephalus (winter))
Bird	BLTE	Black Tern (Chlidonias niger)
Bird	BOBO	Bobolink (Dolichonyx oryzivorus)
Bird	BOOW	Boreal Owl (Aegolius funereus)
Bird	BRFI	Black Rosy-Finch (Leucosticte atrata)
Bird	BRSP	Brewer's Sparrow (Spizella breweri)
Bird	BUOW	Burrowing Owl (Athene cunicularia)
Bird	BUSH	Bushtit (Psaltriparus minimus)
Bird	CABA	Canvasback (Aythya valisineria)
Bird	CATE	Caspian Tern (Sterna caspia)
Bird	CCLS	Chestnut-collared Longspur (Calcarius ornatus)
Bird	CLGR	Clark's Grebe (Aechmophorus clarkii)
Bird	COLO	Common Loon (Gavia immer)
Bird	CSTG	Columbian Sharp-tailed Grouse (Tympanuchus phasianellus columbianus)
Bird	DICK	Dickcissel (Spiza americana)

Taxonomic Class	Species Code	Species
Bird	FEHA	Ferruginous Hawk (Buteo regalis)
Bird	FOTE	Forster's Tern (Sterna forsteri)
Bird	FRGU	Franklin’s Gull (Larus pipixcan)
Bird	GBHE	Great Blue Heron (Ardea herodias)
Bird	GGOW	Great Gray Owl (Strix nebulosa)
Bird	GRSP	Grasshopper Sparrow (Ammodramus savannarum)
Bird	GSGR	Greater Sage-Grouse (Centrocercus urophasianus)
Bird	GSHC	Greater Sandhill Crane (Grus canadensis)
Bird	HADU	Harlequin Duck (Histrionicus histrionicus)
Bird	JUTI	Juniper Titmouse (Baeolophus ridgwayi)
Bird	LABU	Lark Bunting (Calamospiza melanocorys)
Bird	LBCU	Long-billed Curlew (Numenius americanus)
Bird	LESC	Lesser Scaup (Aythya affinis)
Bird	LEWO	Lewis' Woodpecker (Melanerpes lewis)
Bird	MCLO	McCown's Longspur (Calcarius mccownii)
Bird	MERL	Merlin (Falco columbarius)
Bird	MOPL	Mountain Plover (Charadrius montanus)
Bird	NOGO	Northern Goshawk (Accipiter gentilis)
Bird	NPOW	Northern Pygmy-Owl (Glaucidium gnoma)
Bird	PEFA	Peregrine Falcon (Falco peregrinus)
Bird	PYNU	Pygmy Nuthatch (Sitta pygmaea)
Bird	REHE	Redhead (Aythya americana)
Bird	SASP	Sage Sparrow (Amphispiza belli)
Bird	SATH	Sage Thrasher (Oreoscoptes montanus)
Bird	SCOR	Scott's Oriole (Icterus parisorum)
Bird	SEOW	Short-eared Owl (Asio flammeus)
Bird	SNEG	Snowy Egret (Egretta thula)
Bird	SWHA	Swainson's Hawk (Buteo swainsoni)
Bird	TRSW	Trumpeter Swan (Cygnus buccinator)
Bird	UPSA	Upland Sandpiper (Bartramia longicauda)
Bird	VIRA	Virginia Rail (Rallus limicola)
Bird	WEGR	Western Grebe (Aechmophorus occidentalis)
Bird	WESJ	Western Scrub-Jay (Aphelocoma californica)
Bird	WFIB	White-faced Ibis (Plegadis chihi)
Bird	WIFC	Willow Flycatcher (Empidonax traillii)
Bird	YBCC	Yellow-billed Cuckoo (Coccyzus americanus)
Mammal	ABSQ	Abert's Squirrel (Sciurus aberti)
Mammal	AMPI	American Pika (Ochotona princeps)
Mammal	BBBA	Big Brown Bat (Eptesicus fuscus)
Mammal	BFFE	Black-footed Ferret (Mustela nigripes)
Mammal	BISH	Bighorn Sheep (Ovis canadensis)
Mammal	BMJM	Bear Lodge Meadow Jumping Mouse (Zapus hudsonius campestris)
Mammal	BTPD	Black-tailed Prairie Dog (Cynomys ludovicianus)
Mammal	CALY	Canada Lynx (Lynx canadensis)
Mammal	CAMO	Canyon Mouse (Peromyscus crinitus)
Mammal	CLCH	Cliff Chipmunk (Neotamias dorsalis)
Mammal	DWSH	Dwarf Shrew (Sorex nanus)
Mammal	ERBA	Eastern Red Bat (Lasiurus borealis)

Taxonomic Class	Species Code	Species
Mammal	FISH	Fisher (Martes pennanti)
Mammal	FRBA	Fringed Myotis (Myotis thysanodes)
Mammal	GBPM	Great Basin Pocket Mouse (Perognathus parvus)
Mammal	GRBE	Grizzly Bear (Ursus arctos)
Mammal	HASH	Hayden's Shrew (Sorex haydeni)
Mammal	HOBA	Hoary Bat (Lasiurus cinereus)
Mammal	HPMO	Hispid Pocket Mouse (Chaetodipus hispidus)
Mammal	IPGO	Idaho Pocket Gopher (Thomomys idahoensis)
Mammal	LBBA	Little Brown Myotis (Myotis lucifugus)
Mammal	LEBA	Long-eared Myotis (Myotis evotis)
Mammal	LEWE	Least Weasel (Mustela nivalis)
Mammal	LLBA	Long-legged Myotis (Myotis volans)
Mammal	MART	Marten (Martes americana)
Mammal	MOOS	Moose (Alces alces)
Mammal	NFSQ	Northern Flying Squirrel (Glaucomys sabrinus)
Mammal	NOBA	Northern Myotis (Myotis septentrionalis)
Mammal	OBPM	Olive-backed Pocket Mouse (Perognathus fasciatus)
Mammal	PABA	Pallid Bat (Antrozous pallidus)
Mammal	PIMO	Pinyon Mouse (Peromyscus truei)
Mammal	PLHM	Plains Harvest Mouse (Reithrodontomys montanus)
Mammal	PMJM	Preble's Meadow Jumping Mouse (Zapus hudsonius preblei)
Mammal	PPGO	Plains Pocket Gopher (Geomys bursarius)
Mammal	PPMO	Plains Pocket Mouse (Perognathus flavescens)
Mammal	PRSH	Preble's Shrew (Sorex preblei)
Mammal	PRVO	Prairie Vole (Microtus ochrogaster)
Mammal	PYRA	Pygmy Rabbit (Brachylagus idahoensis)
Mammal	PYSH	Pygmy Shrew (Sorex hoyi)
Mammal	RING	Ringtail (Bassariscus astutus)
Mammal	RIOT	River Otter (Lontra canadensis)
Mammal	SBVO	Sagebrush Vole (Lemmiscus curtatus)
Mammal	SFBA	Western Small-footed Myotis (Myotis ciliolabrum)
Mammal	SGSQ	Spotted Ground Squirrel (Spermophilus spilosoma)
Mammal	SHBA	Silver-haired Bat (Lasionycteris noctivagans)
Mammal	SPBA	Spotted Bat (Euderma maculatum)
Mammal	SPMO	Silky Pocket Mouse (Perognathus flavus)
Mammal	SWFO	Swift Fox (Vulpes velox)
Mammal	TBEB	Townsend's Big-eared Bat (Corynorhinus townsendii)
Mammal	UGSQ	Uinta Ground Squirrel (Spermophilus armatus)
Mammal	UNCH	Unita Chipmunk (Neotamias umbrinus)
Mammal	VASH	Vagrant Shrew (Sorex vagrans)
Mammal	WASH	Water Shrew (Sorex palustris)
Mammal	WAVO	Water Vole (Microtus richardsoni)
Mammal	WGSQ	Wyoming Ground Squirrel (Spermophilus elegans)
Mammal	WHVO	Western Heather Vole (Phenacomys intermedius)
Mammal	WOLV	Wolverine (Gulo gulo)
Mammal	WPGO	Wyoming Pocket Gopher (Thomomys clusius)
Mammal	WTPD	White-tailed Prairie Dog (Cynomys leucurus)
Mammal	YPCH	Yellow-pine Chipmunk (Neotamias amoenus)

Taxonomic Class	Species Code	Species
Reptile	BHRS	Black Hills Redbelly Snake (Storeria occipitomaculata pahasapae)
Reptile	BULL	Bullsnake (Pituophis catenifer sayi)
Reptile	EYBR	Eastern Yellow-bellied Racer (Coluber constrictor flaviventris)
Reptile	GBGS	Great Basin Gophersnake (Pituophis catenifer deserticola)
Reptile	GPEL	Great Plains Earless Lizard (Holbrookia maculata)
Reptile	GSHO	Greater Short-horned Lizard (Phrynosoma hernandesi)
Reptile	MFRS	Midget Faded Rattlesnake (Crotalus oreganus concolor)
Reptile	NMLS	Northern Many-lined Skink (Eumeces multivirgatus)
Reptile	NSBL	Northern Sagebrush Lizard (Sceloporus graciosus graciosus)
Reptile	NTLI	Northern Tree Lizard (Urosaurus ornatus wrighti)
Reptile	PAMS	Pale Milksnake (Lampropeltis triangulum multistriata)
Reptile	PFLI	Plateau Fence Lizard (Sceloporus tristichus)
Reptile	PHNS	Plains Hog-nosed Snake (Heterodon nasicus)
Reptile	PLGA	Plains Gartersnake (Thamnophis radix)
Reptile	PRLI	Prairie Lizard (Sceloporus consobrinus)
Reptile	PRRR	Prairie Racerunner (Aspidoscelis sexlineatus viridis)
Reptile	PRRS	Prairie Rattlesnake (Crotalus viridis)
Reptile	RSGS	Red-sided Gartersnake (Thamnophis sirtalis parietalis)
Reptile	RUBO	Rubber Boa (Charina bottae)
Reptile	SGSN	Smooth Green Snake (Opheodrys vernalis)
Reptile	VAGS	Valley Gartersnake (Thamnophis sirtalis fitchi)
Reptile	WAGS	Wandering Gartersnake (Thamnophis elegans vagrans)
Reptile	WPTU	Western Painted Turtle (Chrysemys picta bellii)
Reptile	WSSS	Western Spiny Softshell (Apalone spinifera hartwegi)

Table A3. Model validation statistics and overall model quality index (MQI) for all 156 species in this study. Species codes are given in Table AAA2. Values following '±' are standard deviations. Numbers in parenthesis indicate the transformation of each value into an uncertainty score on a scale of 0 (low uncertainty) to 1 (high uncertainty), where such transformation was necessary.

Taxonomic Group	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Mean Boyce Index;BI	MQI
Amphibian	TISA	228 (1)	9.55 ± 2.94 (0.69)	0.71 ± 0.04	0.35 ± 0.12 (0.65)	Low (0)	0.85 ± 0.11	0.68
Amphibian	BOTO	256 (1)	8.97 ± 3 (0.62)	0.91 ± 0.02	0.03 ± 0.03 (0.97)	High (1)	0.76 ± 0.13	0.87
Amphibian	GPTO	20 (0.5)	9.65 ± 2.83 (0.71)	0.95 ± 0.05	0.15 ± 0.24 (0.85)	Medium (0.5)	na	0.59
Amphibian	RMTO	106 (1)	10.36 ± 2.87 (0.79)	0.91 ± 0.03	0.14 ± 0.1 (0.86)	Medium (0.5)	0.82 ± 0.27	0.83
Amphibian	WYTO	10 (0)	6.1 ± 2.56 (0.26)	0.99 ± 0.02	0.2 ± 0.42 (0.8)	Medium (0.5)	na	0.38
Amphibian	BCFR	97 (0.75)	7.88 ± 2.78 (0.48)	0.7 ± 0.06	0.42 ± 0.19 (0.58)	Low (0)	0.62 ± 0.32	0.54
Amphibian	SLSP	37 (0.5)	7.84 ± 2.73 (0.48)	0.77 ± 0.09	0.29 ± 0.15 (0.71)	Low (0)	na	0.42
Amphibian	GBSP	27 (0.5)	7.96 ± 2.36 (0.5)	0.88 ± 0.07	0.12 ± 0.19 (0.88)	Medium (0.5)	na	0.54
Amphibian	AMBU	3 (0)	4.67 ± 0.58 (0.08)	0.3 ± 0.48	0.67 ± 0.58 (0.33)	Low (0)	na	0.11
Amphibian	NLFR	225 (1)	9.8 ± 2.84 (0.72)	0.81 ± 0.06	0.29 ± 0.13 (0.71)	Medium (0.5)	0.96 ± 0.07	0.8
Amphibian	WOFR	62 (0.75)	10.32 ± 2.02 (0.79)	0.98 ± 0.02	0.05 ± 0.08 (0.95)	Medium (0.5)	0.78 ± 0.23	0.79
Amphibian	CSFR	291 (1)	10.33 ± 2.26 (0.79)	0.94 ± 0.01	0.02 ± 0.01 (0.98)	Medium (0.5)	0.67 ± 0.3	0.83
Bird	COLO	98 (0.75)	6.42 ± 2.21 (0.3)	0.95 ± 0.02	0.13 ± 0.14 (0.87)	Medium (0.5)	0.66 ± 0.37	0.65
Bird	WEGR	144 (1)	5.29 ± 1.38 (0.16)	0.87 ± 0.03	0.2 ± 0.1 (0.8)	Low (0)	0.82 ± 0.13	0.6
Bird	CLGR	29 (0.5)	6.45 ± 2.13 (0.31)	0.88 ± 0.12	0.28 ± 0.31 (0.72)	Low (0)	na	0.4
Bird	AWPE	430 (1)	6.41 ± 1.89 (0.3)	0.82 ± 0.04	0.22 ± 0.06 (0.78)	Medium (0.5)	0.93 ± 0.13	0.71
Bird	AMBI	60 (0.75)	5.45 ± 1.68 (0.18)	0.65 ± 0.12	0.47 ± 0.23 (0.53)	Medium (0.5)	0.75 ± 0.27	0.55
Bird	GBHE	847 (1)	5.65 ± 1.32 (0.21)	0.69 ± 0.02	0.33 ± 0.04 (0.67)	Medium (0.5)	0.97 ± 0.05	0.66
Bird	SNEG	43 (0.5)	5.3 ± 1.47 (0.16)	0.91 ± 0.04	0.17 ± 0.17 (0.84)	Medium (0.5)	0.95 ± 0.07	0.6
Bird	BCNH	76 (0.75)	5.93 ± 1.8 (0.24)	0.88 ± 0.06	0.12 ± 0.1 (0.88)	Medium (0.5)	0.67 ± 0.38	0.63

Taxonomic Group	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Mean Boyce Index;BI	MQI
Bird	WFIB	89 (0.75)	5.97 ± 2.03 (0.25)	0.74 ± 0.06	0.36 ± 0.19 (0.64)	Medium (0.5)	0.9 ± 0.12	0.61
Bird	TRSW	165 (1)	6.67 ± 2.06 (0.33)	0.95 ± 0.01	0.09 ± 0.09 (0.91)	Medium (0.5)	0.34 ± 0.13	0.67
Bird	CABA	62 (0.75)	5.66 ± 1.33 (0.21)	0.73 ± 0.09	0.36 ± 0.25 (0.64)	Low (0)	0.63 ± 0.32	0.49
Bird	REHE	99 (0.75)	5.69 ± 1.72 (0.21)	0.76 ± 0.06	0.18 ± 0.1 (0.82)	Medium (0.5)	0.73 ± 0.28	0.61
Bird	LESC	102 (1)	5.43 ± 1.35 (0.18)	0.64 ± 0.1	0.36 ± 0.15 (0.64)	Low (0)	0.43 ± 0.37	0.5
Bird	HADU	47 (0.5)	6.45 ± 2.06 (0.31)	0.94 ± 0.06	0.14 ± 0.19 (0.86)	Medium (0.5)	0.56 ± 0.45	0.58
Bird	BAGO	61 (0.75)	5.46 ± 1.4 (0.18)	0.87 ± 0.04	0.23 ± 0.21 (0.77)	Medium (0.5)	0.5 ± 0.34	0.58
Bird	BESU	353 (1)	6.36 ± 1.93 (0.29)	0.72 ± 0.04	0.34 ± 0.13 (0.66)	High (1)	0.92 ± 0.09	0.75
Bird	BEWI	2794 (1)	5.49 ± 1.53 (0.19)	0.69 ± 0.01	0.32 ± 0.04 (0.68)	Medium (0.5)	0.9 ± 0.08	0.65
Bird	NOGO	421 (1)	6.58 ± 2.41 (0.32)	0.89 ± 0.02	0.17 ± 0.06 (0.83)	High (1)	0.92 ± 0.1	0.8
Bird	SWHA	861 (1)	5.64 ± 1.6 (0.2)	0.69 ± 0.02	0.35 ± 0.09 (0.65)	Medium (0.5)	0.94 ± 0.05	0.65
Bird	FEHA	1443 (1)	6.12 ± 1.92 (0.26)	0.74 ± 0.02	0.24 ± 0.1 (0.76)	Medium (0.5)	1 ± 0	0.7
Bird	MERL	182 (1)	6.35 ± 2.28 (0.29)	0.63 ± 0.07	0.64 ± 0.15 (0.36)	Medium (0.5)	0.6 ± 0.29	0.58
Bird	PEFA	181 (1)	7.39 ± 2.58 (0.42)	0.68 ± 0.05	0.37 ± 0.1 (0.63)	Medium (0.5)	0.81 ± 0.17	0.68
Bird	GSGR	1610 (1)	7.87 ± 1.48 (0.48)	0.86 ± 0.01	0.09 ± 0.03 (0.91)	Medium (0.5)	0.88 ± 0.14	0.77
Bird	CSTG	40 (0.5)	8.38 ± 2.82 (0.55)	0.98 ± 0.03	0.13 ± 0.18 (0.88)	High (1)	0.98 ± 0.06	0.77
Bird	VIRA	16 (0)	6.31 ± 1.54 (0.29)	0.76 ± 0.16	0.45 ± 0.37 (0.55)	Low (0)	1 ± 0	0.39
Bird	GSHC	1181 (1)	6.54 ± 1.88 (0.32)	0.75 ± 0.02	0.25 ± 0.03 (0.75)	Low (0)	0.97 ± 0.05	0.64
Bird	MOPL	302 (1)	8.63 ± 2.91 (0.58)	0.81 ± 0.04	0.23 ± 0.12 (0.77)	High (1)	0.9 ± 0.12	0.84
Bird	UPSA	120 (1)	6.08 ± 1.66 (0.26)	0.92 ± 0.02	0.11 ± 0.14 (0.89)	Medium (0.5)	0.78 ± 0.24	0.71
Bird	LBCU	341 (1)	6.17 ± 1.77 (0.27)	0.74 ± 0.05	0.35 ± 0.09 (0.65)	Medium (0.5)	1 ± 0	0.68
Bird	FRGU	33 (0.5)	4.97 ± 1.33 (0.12)	0.86 ± 0.08	0.29 ± 0.3 (0.71)	Medium (0.5)	na	0.43
Bird	CATE	33 (0.5)	5.91 ± 2.1 (0.24)	0.92 ± 0.07	0.17 ± 0.22 (0.83)	Medium (0.5)	na	0.48

Taxonomic Group	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Mean Boyce Index;BI	MQI
Bird	FOTE	35 (0.5)	6.51 ± 2.13 (0.31)	0.85 ± 0.13	0.28 ± 0.27 (0.73)	Medium (0.5)	na	0.47
Bird	BLTE	42 (0.5)	5.33 ± 1.48 (0.17)	0.83 ± 0.1	0.17 ± 0.19 (0.84)	Low (0)	0.93 ± 0.09	0.51
Bird	YBCC	19 (0)	6.79 ± 2.18 (0.35)	0.94 ± 0.04	0.25 ± 0.35 (0.75)	Low (0)	na	0.32
Bird	NPOW	11 (0)	7 ± 1.41 (0.38)	0.95 ± 0.05	0.1 ± 0.32 (0.9)	Medium (0.5)	na	0.42
Bird	BUOW	655 (1)	6.9 ± 2.41 (0.36)	0.78 ± 0.02	0.22 ± 0.05 (0.78)	High (1)	0.93 ± 0.07	0.79
Bird	GGOW	55 (0.75)	6.07 ± 1.74 (0.26)	0.92 ± 0.05	0.11 ± 0.16 (0.89)	High (1)	0.54 ± 0.3	0.69
Bird	SEOW	142 (1)	6.26 ± 1.81 (0.28)	0.73 ± 0.05	0.35 ± 0.1 (0.65)	Medium (0.5)	0.74 ± 0.25	0.65
Bird	BOOW	58 (0.75)	9.36 ± 1.98 (0.67)	0.94 ± 0.03	0.05 ± 0.11 (0.95)	High (1)	0.43 ± 0.37	0.78
Bird	LEWO	118 (1)	5.84 ± 1.55 (0.23)	0.88 ± 0.06	0.24 ± 0.12 (0.76)	Medium (0.5)	0.85 ± 0.16	0.69
Bird	BBWP	11 (0)	7.73 ± 2.69 (0.47)	0.95 ± 0.07	0.1 ± 0.32 (0.9)	Medium (0.5)	na	0.44
Bird	ATTW	110 (1)	9.94 ± 2.72 (0.74)	0.95 ± 0.02	0.09 ± 0.14 (0.91)	High (1)	0.75 ± 0.31	0.89
Bird	WIFC	95 (0.75)	6.24 ± 1.91 (0.28)	0.68 ± 0.08	0.45 ± 0.18 (0.55)	Low (0)	0.59 ± 0.24	0.48
Bird	ATFC	60 (0.75)	6.55 ± 2.73 (0.32)	0.9 ± 0.04	0.18 ± 0.17 (0.82)	Medium (0.5)	0.82 ± 0.16	0.66
Bird	WESJ	26 (0.5)	7.42 ± 2.8 (0.43)	0.97 ± 0.04	0.12 ± 0.19 (0.88)	Medium (0.5)	na	0.54
Bird	JUTI	31 (0.5)	8.48 ± 3.03 (0.56)	0.97 ± 0.03	0.15 ± 0.25 (0.85)	Medium (0.5)	na	0.56
Bird	BUSH	24 (0.5)	8.33 ± 3.67 (0.54)	0.91 ± 0.07	0.1 ± 0.21 (0.9)	Medium (0.5)	na	0.55
Bird	PYNU	35 (0.5)	6.63 ± 2.66 (0.33)	0.94 ± 0.07	0.13 ± 0.19 (0.87)	Medium (0.5)	na	0.51
Bird	SATH	635 (1)	8.95 ± 2.5 (0.62)	0.69 ± 0.03	0.19 ± 0.07 (0.81)	High (1)	0.69 ± 0.24	0.8
Bird	DICK	24 (0.5)	7.67 ± 2.32 (0.46)	0.95 ± 0.05	0 ± 0 (1)	Medium (0.5)	na	0.56
Bird	BRSP	1372 (1)	8.8 ± 2.54 (0.6)	0.65 ± 0.02	0.26 ± 0.05 (0.74)	High (1)	0.82 ± 0.2	0.8
Bird	SASP	631 (1)	8.21 ± 2.83 (0.53)	0.78 ± 0.02	0.19 ± 0.06 (0.81)	High (1)	0.88 ± 0.13	0.82
Bird	LABU	407 (1)	6.02 ± 1.5 (0.25)	0.71 ± 0.02	0.28 ± 0.14 (0.72)	High (1)	0.71 ± 0.28	0.72
Bird	GRSP	261 (1)	7.79 ± 1.75 (0.47)	0.82 ± 0.03	0.26 ± 0.06 (0.74)	High (1)	0.82 ± 0.28	0.8

Taxonomic Group	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Mean Boyce Index;BI	MQI
Bird	MCLO	152 (1)	8.24 ± 2.63 (0.53)	0.9 ± 0.03	0.17 ± 0.11 (0.83)	High (1)	0.84 ± 0.15	0.84
Bird	CCLS	90 (0.75)	7.38 ± 2.31 (0.42)	0.89 ± 0.05	0.22 ± 0.19 (0.78)	High (1)	0.9 ± 0.09	0.76
Bird	BOBO	46 (0.5)	6.72 ± 1.8 (0.34)	0.83 ± 0.11	0.27 ± 0.23 (0.74)	Medium (0.5)	0.84 ± 0.22	0.6
Bird	SCOR	9 (0)	6.56 ± 3.21 (0.32)	0.88 ± 0.31	0.22 ± 0.44 (0.78)	Medium (0.5)	na	0.38
Bird	BRFI	7 (0)	7.86 ± 2.19 (0.48)	0.65 ± 0.46	0.29 ± 0.49 (0.71)	Low (0)	na	0.3
Bird	BCRF	2 (0)	9 ± 2.83 (0.63)	0.15 ± 0.34	0.5 ± 0.71 (0.5)	Low (0)	na	0.23
Mammal	PRSH	3 (0)	4.33 ± 3.51 (0.04)	0.3 ± 0.48	1 ± 0 (0)	Low (0)	na	0.05
Mammal	VASH	22 (0.5)	4.86 ± 1.04 (0.11)	0.82 ± 0.18	0.33 ± 0.33 (0.67)	Low (0)	na	0.34
Mammal	DWSH	15 (0)	5.8 ± 1.7 (0.23)	0.75 ± 0.27	0.5 ± 0.47 (0.5)	Medium (0.5)	na	0.3
Mammal	WASH	23 (0.5)	5.22 ± 1.31 (0.15)	0.85 ± 0.07	0.18 ± 0.24 (0.82)	Medium (0.5)	na	0.45
Mammal	PYSH	5 (0)	5.8 ± 1.64 (0.23)	0.5 ± 0.52	0.2 ± 0.45 (0.8)	Low (0)	na	0.23
Mammal	HASH	14 (0)	6.21 ± 2.26 (0.28)	0.97 ± 0.04	0.05 ± 0.16 (0.95)	Medium (0.5)	na	0.41
Mammal	LBBA	119 (1)	7.18 ± 3.54 (0.4)	0.75 ± 0.05	0.29 ± 0.14 (0.71)	Medium (0.5)	0.78 ± 0.16	0.69
Mammal	LEBA	60 (0.75)	7.55 ± 3.15 (0.44)	0.8 ± 0.1	0.28 ± 0.24 (0.72)	Medium (0.5)	0.69 ± 0.33	0.64
Mammal	FRBA	24 (0.5)	10.25 ± 2.36 (0.78)	0.94 ± 0.03	0.12 ± 0.19 (0.88)	Medium (0.5)	na	0.61
Mammal	LLBA	80 (0.75)	8.51 ± 3.26 (0.56)	0.8 ± 0.11	0.35 ± 0.23 (0.65)	Medium (0.5)	0.82 ± 0.23	0.68
Mammal	SFBA	66 (0.75)	7.39 ± 2.58 (0.42)	0.8 ± 0.08	0.32 ± 0.18 (0.68)	Medium (0.5)	0.75 ± 0.31	0.64
Mammal	NOBA	3 (0)	8.67 ± 2.89 (0.58)	0.28 ± 0.45	0 ± 0 (1)	Low (0)	na	0.31
Mammal	SHBA	63 (0.75)	7.92 ± 3.57 (0.49)	0.8 ± 0.08	0.27 ± 0.17 (0.73)	Medium (0.5)	0.88 ± 0.18	0.68
Mammal	BBBA	83 (0.75)	6.94 ± 3.37 (0.37)	0.74 ± 0.07	0.26 ± 0.15 (0.74)	Medium (0.5)	0.67 ± 0.32	0.62
Mammal	ERBA	5 (0)	5.4 ± 1.67 (0.18)	0.37 ± 0.41	0 ± 0 (1)	Low (0)	na	0.23
Mammal	HOBA	63 (0.75)	8.81 ± 3.23 (0.6)	0.83 ± 0.06	0.24 ± 0.08 (0.76)	Medium (0.5)	0.82 ± 0.26	0.71
Mammal	SPBA	14 (0)	9.57 ± 2.14 (0.7)	0.98 ± 0.03	0.2 ± 0.42 (0.8)	Medium (0.5)	na	0.47

Taxonomic Group	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Mean Boyce Index;BI	MQI
Mammal	TBEB	50 (0.75)	7.92 ± 1.95 (0.49)	0.9 ± 0.1	0.16 ± 0.16 (0.84)	Medium (0.5)	0.84 ± 0.22	0.71
Mammal	PABA	16 (0)	7.38 ± 2.5 (0.42)	0.79 ± 0.24	0.3 ± 0.48 (0.7)	Medium (0.5)	na	0.37
Mammal	AMPI	170 (1)	6.08 ± 1.97 (0.26)	0.96 ± 0.02	0.11 ± 0.08 (0.89)	High (1)	0.65 ± 0.25	0.77
Mammal	PYRA	278 (1)	10.39 ± 2.4 (0.8)	0.93 ± 0.01	0.09 ± 0.07 (0.91)	High (1)	0.86 ± 0.14	0.91
Mammal	YPCH	12 (0)	4.25 ± 2.22 (0.03)	0.89 ± 0.09	0.35 ± 0.47 (0.65)	Medium (0.5)	na	0.3
Mammal	CLCH	8 (0)	6.25 ± 1.39 (0.28)	0.79 ± 0.42	0.13 ± 0.35 (0.88)	Low (0)	na	0.3
Mammal	UNCH	16 (0)	4.25 ± 2.27 (0.03)	0.84 ± 0.16	0.06 ± 0.02 (0.94)	Medium (0.5)	na	0.33
Mammal	UGSQ	67 (0.75)	6.88 ± 3.14 (0.36)	0.88 ± 0.03	0.2 ± 0.1 (0.8)	Low (0)	0.47 ± 0.3	0.54
Mammal	SGSQ	13 (0)	5.46 ± 2.07 (0.18)	0.91 ± 0.18	0.45 ± 0.38 (0.55)	Medium (0.5)	na	0.32
Mammal	WGSQ	268 (1)	6.13 ± 2.16 (0.27)	0.82 ± 0.04	0.17 ± 0.1 (0.83)	Low (0)	0.48 ± 0.34	0.58
Mammal	BTPD	1132 (1)	12 ± 0 (1)	0.88 ± 0.01	0.03 ± 0.01 (0.97)	High (1)	0.18 ± 0.18	0.86
Mammal	WTPD	1175 (1)	6.1 ± 2.05 (0.26)	0.8 ± 0.01	0.06 ± 0.03 (0.94)	High (1)	0.07 ± 0.09	0.67
Mammal	ABSQ	4 (0)	5.25 ± 1.5 (0.16)	0.4 ± 0.52	0.25 ± 0.5 (0.75)	Medium (0.5)	na	0.27
Mammal	NFSQ	21 (0.5)	5.57 ± 1.5 (0.2)	0.92 ± 0.06	0.27 ± 0.44 (0.73)	Medium (0.5)	na	0.46
Mammal	WPGO	15 (0)	8.47 ± 3.52 (0.56)	0.97 ± 0.04	0.2 ± 0.42 (0.8)	Medium (0.5)	na	0.44
Mammal	IPGO	27 (0.5)	4.52 ± 1.16 (0.06)	0.97 ± 0.04	0.1 ± 0.22 (0.9)	Medium (0.5)	na	0.46
Mammal	PPGO	3 (0)	5 ± 1 (0.13)	0.28 ± 0.46	0.33 ± 0.58 (0.67)	Low (0)	na	0.16
Mammal	OBPM	28 (0.5)	5.89 ± 2.13 (0.24)	0.67 ± 0.13	0.47 ± 0.36 (0.53)	Medium (0.5)	na	0.4
Mammal	PPMO	11 (0)	7.91 ± 2.21 (0.49)	0.91 ± 0.1	0.15 ± 0.34 (0.85)	Medium (0.5)	na	0.43
Mammal	SPMO	3 (0)	4.67 ± 0.58 (0.08)	0.99 ± 0.01	0.67 ± 0.58 (0.33)	Low (0)	na	0.21
Mammal	GBPM	17 (0)	6.18 ± 2.48 (0.27)	0.93 ± 0.05	0.1 ± 0.21 (0.9)	Medium (0.5)	na	0.39
Mammal	HPMO	10 (0)	5.4 ± 2.22 (0.18)	0.98 ± 0.02	0.3 ± 0.48 (0.7)	Medium (0.5)	na	0.35
Mammal	PLHM	7 (0)	6.43 ± 3.1 (0.3)	0.65 ± 0.45	0.43 ± 0.53 (0.57)	Low (0)	na	0.24

Taxonomic Group	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Mean Boyce Index;BI	MQI
Mammal	CAMO	3 (0)	4.67 ± 1.15 (0.08)	0.3 ± 0.48	0.67 ± 0.58 (0.33)	Low (0)	na	0.11
Mammal	PIMO	2 (0)	4 ± 0 (0)	0.1 ± 0.21	0 ± 0 (1)	Low (0)	na	0.16
Mammal	WHVO	7 (0)	5.29 ± 0.76 (0.16)	0.69 ± 0.47	0.14 ± 0.38 (0.86)	Low (0)	na	0.26
Mammal	PRVO	24 (0.5)	5.75 ± 1.39 (0.22)	0.78 ± 0.12	0.32 ± 0.34 (0.68)	Medium (0.5)	na	0.44
Mammal	WAVO	77 (0.75)	6.06 ± 2.36 (0.26)	0.94 ± 0.02	0.14 ± 0.14 (0.86)	Medium (0.5)	0.75 ± 0.21	0.65
Mammal	SBVO	31 (0.5)	5.71 ± 2.42 (0.21)	0.76 ± 0.1	0.33 ± 0.27 (0.68)	Medium (0.5)	na	0.43
Mammal	PMJM	48 (0.5)	10.44 ± 2.4 (0.8)	0.98 ± 0.01	0.04 ± 0.08 (0.96)	High (1)	0.83 ± 0.28	0.82
Mammal	BMJM	20 (0.5)	6.05 ± 3.53 (0.26)	0.98 ± 0.03	0.1 ± 0.21 (0.9)	Medium (0.5)	na	0.5
Mammal	SWFO	223 (1)	6.64 ± 1.68 (0.33)	0.94 ± 0.02	0.13 ± 0.06 (0.87)	High (1)	0.88 ± 0.13	0.81
Mammal	GRBE	639 (1)	7.07 ± 1.22 (0.38)	0.94 ± 0	0.04 ± 0.03 (0.96)	High (1)	0.64 ± 0.31	0.8
Mammal	RING	7 (0)	7.14 ± 2.04 (0.39)	0.63 ± 0.44	0.29 ± 0.49 (0.71)	Low (0)	na	0.28
Mammal	MART	202 (1)	6.4 ± 1.8 (0.3)	0.94 ± 0.01	0.07 ± 0.05 (0.93)	High (1)	0.76 ± 0.19	0.8
Mammal	FISH	14 (0)	4.93 ± 2.56 (0.12)	0.91 ± 0.09	0.2 ± 0.42 (0.8)	Medium (0.5)	na	0.34
Mammal	LEWE	9 (0)	6.22 ± 2.33 (0.28)	0.99 ± 0.01	0.11 ± 0.33 (0.89)	Medium (0.5)	na	0.4
Mammal	BFFE	4 (0)	5.25 ± 2.5 (0.16)	0.38 ± 0.49	0.5 ± 0.58 (0.5)	Low (0)	na	0.16
Mammal	WOLV	192 (1)	6.16 ± 2.5 (0.27)	0.92 ± 0.03	0.12 ± 0.08 (0.88)	High (1)	0.06 ± 0.66	0.68
Mammal	RIOT	202 (1)	6.46 ± 2.5 (0.31)	0.86 ± 0.04	0.24 ± 0.09 (0.76)	Medium (0.5)	0.99 ± 0.03	0.73
Mammal	CALY	232 (1)	5.84 ± 1.54 (0.23)	0.93 ± 0.03	0.1 ± 0.09 (0.9)	High (1)	0.69 ± 0.33	0.77
Mammal	MOOS	4930 (1)	6.73 ± 1.44 (0.34)	0.64 ± 0.01	0.18 ± 0.02 (0.82)	High (1)	0.97 ± 0.05	0.78
Mammal	BISH	1716 (1)	6.76 ± 1.47 (0.34)	0.8 ± 0.02	0.24 ± 0.03 (0.76)	High (1)	0.98 ± 0.04	0.79
Reptile	WPTU	21 (0.5)	9.43 ± 2.48 (0.68)	0.93 ± 0.06	0.2 ± 0.35 (0.8)	Low (0)	na	0.5
Reptile	WSSS	19 (0)	7.42 ± 2.67 (0.43)	0.85 ± 0.16	0.25 ± 0.35 (0.75)	Low (0)	na	0.32
Reptile	GPEL	7 (0)	5.43 ± 1.4 (0.18)	0.69 ± 0.47	0.43 ± 0.53 (0.57)	Low (0)	na	0.22

Taxonomic Group	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Mean Boyce Index;BI	MQI
Reptile	GSHO	148 (1)	8.11 ± 2.47 (0.51)	0.81 ± 0.05	0.19 ± 0.13 (0.81)	High (1)	na	0.7
Reptile	NSBL	112 (1)	9.54 ± 3 (0.69)	0.86 ± 0.05	0.19 ± 0.13 (0.81)	Medium (0.5)	0.79 ± 0.17	0.79
Reptile	PFLI	34 (0.5)	7.26 ± 3.6 (0.41)	0.92 ± 0.04	0.29 ± 0.23 (0.71)	Low (0)	na	0.43
Reptile	PRLI	3 (0)	7 ± 1.73 (0.38)	0.3 ± 0.48	0.33 ± 0.58 (0.67)	Low (0)	na	0.22
Reptile	NTLI	13 (0)	7.62 ± 3.25 (0.45)	0.99 ± 0.01	0.05 ± 0.16 (0.95)	Medium (0.5)	na	0.44
Reptile	NMLS	6 (0)	4.17 ± 0.41 (0.02)	0.97 ± 0.5	0.5 ± 0.55 (0.5)	Low (0)	na	0.21
Reptile	PRRR	4 (0)	4.5 ± 1 (0.06)	0.4 ± 0.51	0.5 ± 0.58 (0.5)	Low (0)	na	0.14
Reptile	RUBO	51 (0.75)	6.9 ± 2.09 (0.36)	0.9 ± 0.04	0.25 ± 0.2 (0.75)	Medium (0.5)	0.86 ± 0.15	0.67
Reptile	EYBR	60 (0.75)	7.63 ± 3.2 (0.45)	0.86 ± 0.06	0.13 ± 0.15 (0.87)	Medium (0.5)	0.79 ± 0.2	0.69
Reptile	PHNS	22 (0.5)	7.32 ± 3.05 (0.41)	0.83 ± 0.13	0 ± 0 (1)	Medium (0.5)	na	0.53
Reptile	PAMS	19 (0)	6.26 ± 1.79 (0.28)	0.9 ± 0.1	0.3 ± 0.26 (0.7)	Low (0)	na	0.29
Reptile	GBGS	15 (0)	6.93 ± 2.79 (0.37)	0.94 ± 0.05	0.1 ± 0.21 (0.9)	Medium (0.5)	na	0.41
Reptile	BULL	145 (1)	8.67 ± 2.82 (0.58)	0.82 ± 0.03	0.21 ± 0.1 (0.79)	Medium (0.5)	0.88 ± 0.09	0.77
Reptile	BHRS	8 (0)	7.75 ± 3.06 (0.47)	0.78 ± 0.41	0.13 ± 0.35 (0.88)	Low (0)	na	0.34
Reptile	WAGS	129 (1)	8.19 ± 3.08 (0.52)	0.7 ± 0.08	0.36 ± 0.14 (0.64)	Low (0)	0.77 ± 0.28	0.63
Reptile	PLGA	18 (0)	6.5 ± 2.92 (0.31)	0.8 ± 0.2	0.35 ± 0.41 (0.65)	Medium (0.5)	na	0.34
Reptile	RSGS	32 (0.5)	7.78 ± 1.91 (0.47)	0.85 ± 0.07	0.27 ± 0.22 (0.73)	Medium (0.5)	na	0.5
Reptile	VAGS	2 (0)	9 ± 1.41 (0.63)	0.1 ± 0.21	0 ± 0 (1)	Low (0)	na	0.29
Reptile	SGSN	24 (0.5)	7.5 ± 2.99 (0.44)	0.92 ± 0.16	0.13 ± 0.32 (0.87)	Medium (0.5)	na	0.53
Reptile	PRRS	281 (1)	6.88 ± 2.07 (0.36)	0.78 ± 0.03	0.36 ± 0.1 (0.64)	Medium (0.5)	0.82 ± 0.11	0.68
Reptile	MFRS	35 (0.5)	9.6 ± 3.28 (0.7)	0.97 ± 0.03	0.03 ± 0.11 (0.97)	Medium (0.5)	na	0.61

Appendix B: Evaluation of exposure calculation assumptions

Impact distance function

Species will likely exhibit differential sensitivities to development, so decay curves of different radii may be appropriate for different taxa. To evaluate the effect of changing the width of the exposure function we also conducted analyses using narrow (200 meter) and wide (5 kilometer) effect distances, chosen to represent a reasonable range derived from the literature (Benitez-Lopez et al. 2010). Analyses using all three exposure functions resulted in similar rankings (Spearman rank correlation: $r_s \geq 0.963$ and $P < 0.001$ for all tests), and although there were some relative rank shifts among species (Fig. B1), they did not alter any of the main conclusions presented in this study. Moreover, rank shifts did not generally move species between categories of concern; species that ranked high using the 1 kilometer effect distance also ranked high using the others. For example, the 10 most highly exposed species remained largely the same with all effect distances. The robustness of our analyses to these different effect distances is partially due to the large-scale clumping of energy resources (Fig. B2), while the spacing of individual disturbance events (e.g., well pads and wind turbines) are typically highly regular within these clumps at scales on the order of roughly 0.5-2 kilometers, resulting in relatively little effect on ranks from altering impact distances.

Relative shifts within the highly-exposed group did, however, present additional reasons to be concerned for some species. For example, Pygmy Rabbit (the 4th most exposed species in the main analysis) was the most exposed species when we used the narrow exposure curve, while Black Footed Ferret (the 6th most exposed species in the main analysis) was the second most-exposed species when we used the wider exposure curve. Wyoming Pocket Gopher (the 5th most exposed species in the main analysis) ranked more highly when either the narrow or wide curve was used.

Energy buildout scenarios

Model fit for both oil and gas and wind-power were very good based on all metrics, giving us high confidence that they are reasonable approximations of potential energy resources in Wyoming relative to the scale of analyses in this study, namely statewide calculations of species impacts. Uncertainty is further reduced by our use of a two-step process (discussed above) where outputs from these models were adjusted to reflect known, near-term indicators of development (e.g., proximity to existing transmission infrastructure and surface exclusions such as wilderness area restrictions). These adjustments increase our confidence in the near-term spatial accuracy of the final buildout scenarios and further insures that our projections of the spatial pattern of energy development will be robust in the near future (i.e., 10-20 years), with higher uncertainty over time horizons beyond the scope of this study.

The most prominent sources of mid and long-term uncertainty are the advent of new technologies that allow development of resources not captured in currently developed sites and fluctuations in national and international energy markets. There is no practical way to objectively assess the former, as it is extremely difficult to predict advancements in technology that will ultimately become economically viable for industrial-scale operations. Regarding markets, the pace and magnitude of development was carefully assessed in the reports that we used to create both buildout maps. Moreover, given the consistently increasing demand for energy both globally and domestically, it is highly likely that most currently-identified petroleum resources will eventually be developed, and that wind-power will continue to be one of the most developed sources of renewable energy in the coming decades (Copeland et al. 2009, EIA 2011a, b, 2012). Since we have good models of where currently extractable resources exist and what near-term factors influence their development, the biggest uncertainty over the time frame of this study is not where development will occur, but how quickly it will cover areas of predicted potential.

To evaluate how uncertainty in the rate and extent of currently feasible development on our estimates, we created unrestrained buildout scenarios for both energy models. For oil and gas, the unrestrained scenario used the Random Forests binary classification (noted above) to place wells at the allowable density in every cell with anticipated petroleum potential, resulting in nearly triple the number of wells from the anticipated scenario (Fig. B2). For the wind-power unrestrained scenario, fewer development projections exist and it is not clear that all, or even most, potential areas will eventually be developed. Therefore, rather than completely develop the resource we doubled the number of new turbines relative to the anticipated scenario (i.e., 9,138 turbines). Using these unrestrained scenarios to calculate exposure did not substantially alter results, as demonstrated by comparing the resulting species ranks to those from the anticipated scenario. As one would expect, the magnitude of exposures increased substantially (Fig. B3) and resulted in some relative rank shifts among species (Fig. B4), but these differences did not significantly alter the rankings (Spearman rank correlation: $r_s = 0.977$, $P < 0.001$) and thus did not alter any of the main conclusions presented in this study. In general, those species deemed at risk when analyzing the anticipated scenario were also deemed at risk in the unrestrained scenario, though the level of concern for some species increases with more development (e.g., Great Basin Spadefoot is the 16th most exposed species in the anticipated scenario, but becomes the 5th most exposed species in the unrestrained scenario).

Since large-scale, commercial development of the nation's wind-power is relatively new, we view the spatial pattern of its near-term expansion as somewhat more uncertain than that for petroleum resources. Fortunately, in the short-term wind power will undoubtedly have a much smaller footprint than that of oil and natural gas and as such will contribute much less to overall exposure for the vast majority of species (Figure B2). The only species for which wind-power development has the potential to substantially impact species viability over the course of this study is Black-Footed Ferret, which is the sixth most exposed species in this study due largely to wind-power development concentrated in the Shirley Basin of central Wyoming. We therefore assessed the variation in the exposure of Black-Footed Ferret caused by spatial uncertainty in wind-power buildout. This was accomplished by creating 10 wind-power potential models from subsets of the full dataset and assessing exposures resulting from each. This yielded a range of EI values from 0.169 to 0.177 (mean 0.172, standard deviation 0.002). Comparing these values to the anticipated EI values of other species (Table C1), this level of variation could shift the rank of Black-footed Ferret between the 6th and 9th most exposed species, which does not alter conclusions for Black-footed Ferret and is thus not expected to substantially change conclusions for other species in this study.

Figures and Tables

Figure B1. Range in exposure ranks resulting from using different exposure functions to quantify exposure to disturbance. Abscissa shows the exposure rank, with 1 being the most exposed to development. Ordinate shows individual species (see Table A1 for codes) ordered by their exposure rank using the 1-kilometer exposure curve (solid circles). Grey bars span the range of possible ranks when further considering the narrow curve (200 meters; open circles) and the wide curve (5 kilometers; open squares). Panels A-D show different subsets of the 156 species analyzed.

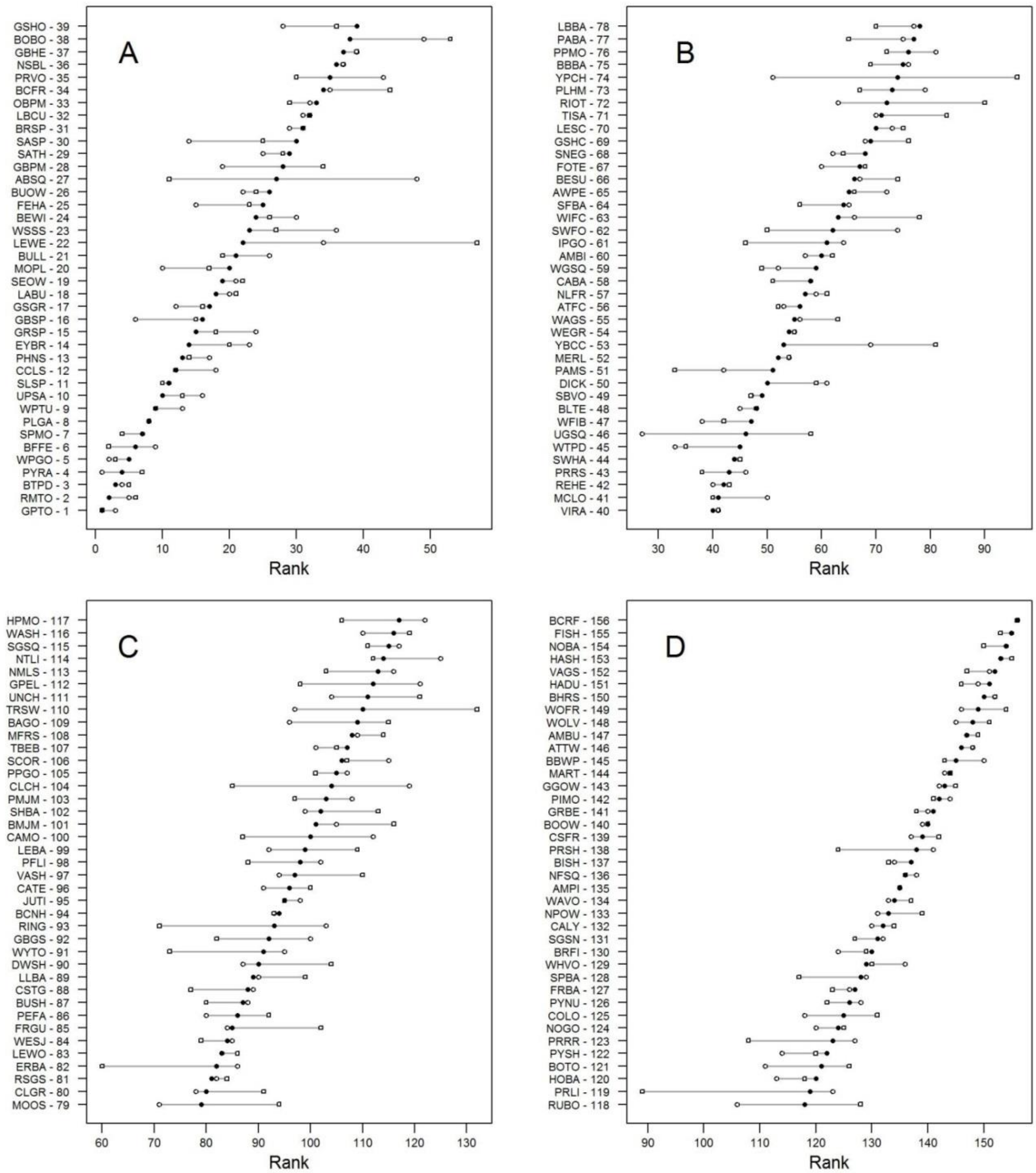


Figure B2. Energy footprint maps of Wyoming showing the 2030 predicted exposure surface for oil and gas wells and wind-power turbines under anticipated (A) and unrestrained (B) scenarios. Data are displayed over a shaded topographic relief map with county boundaries for reference.

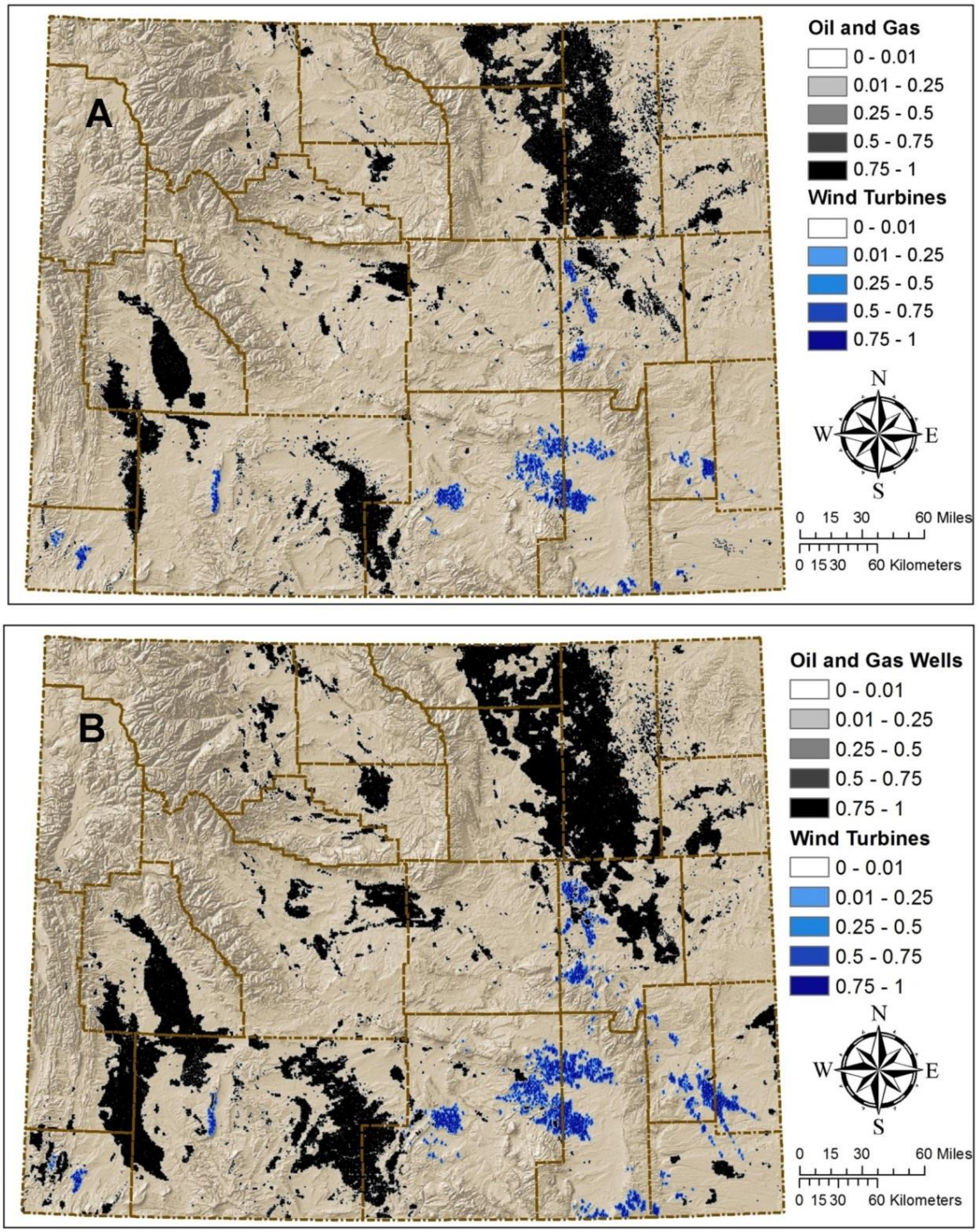


Figure B3. Projected 2030 total Exposure Index (EI) for 156 Wyoming Species of Greatest Conservation Need (SGCN) examined in this study under the anticipated (hollow bars) and unrestrained (gray squares) buildout scenarios. Ordinate shows individual species (codes provided in Table A1) ordered by their exposure rank under the anticipated scenario. Dotted lines represent the difference in EI between the scenarios. Panels A-D show subsets of the 156 species analyzed.

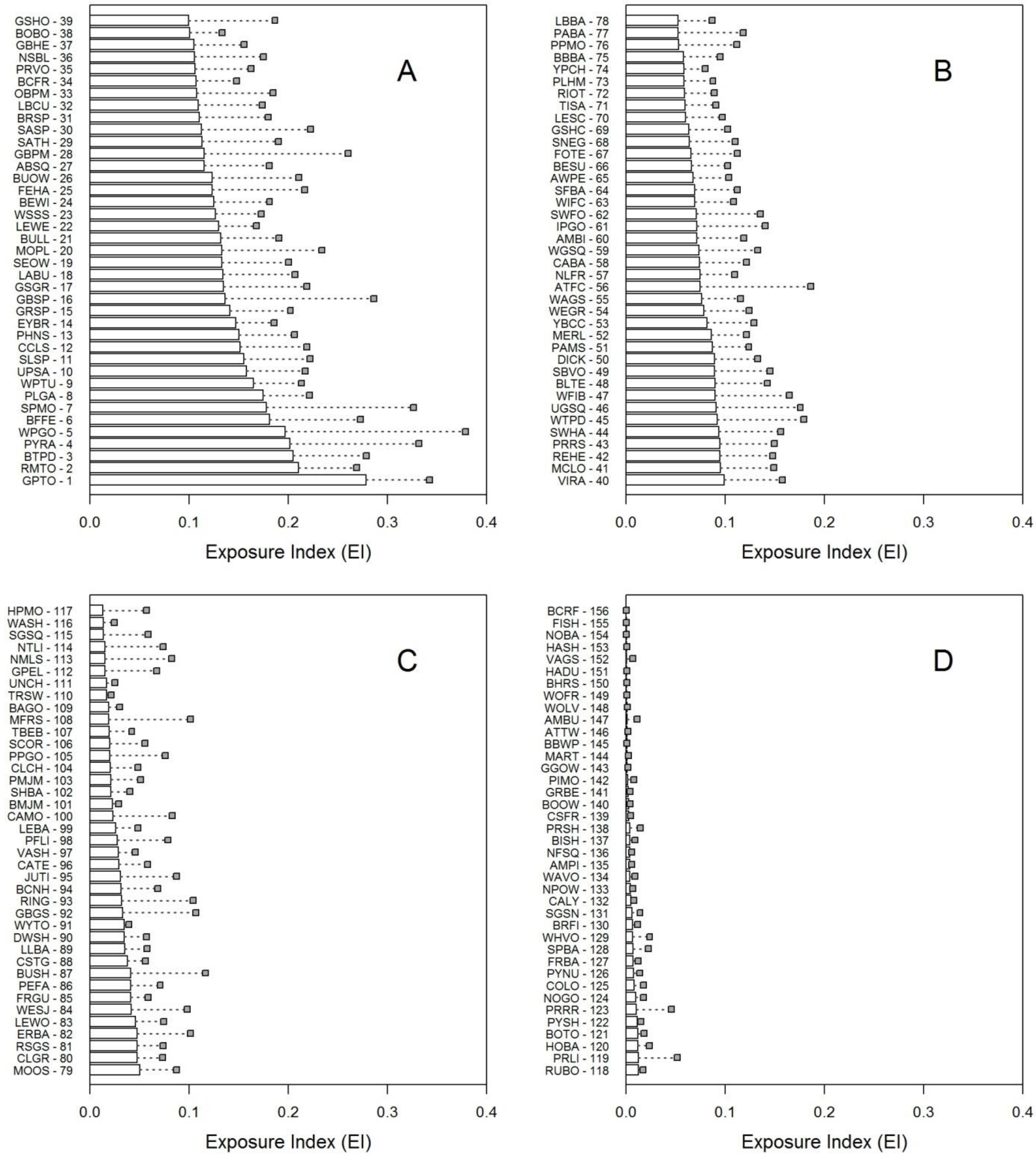
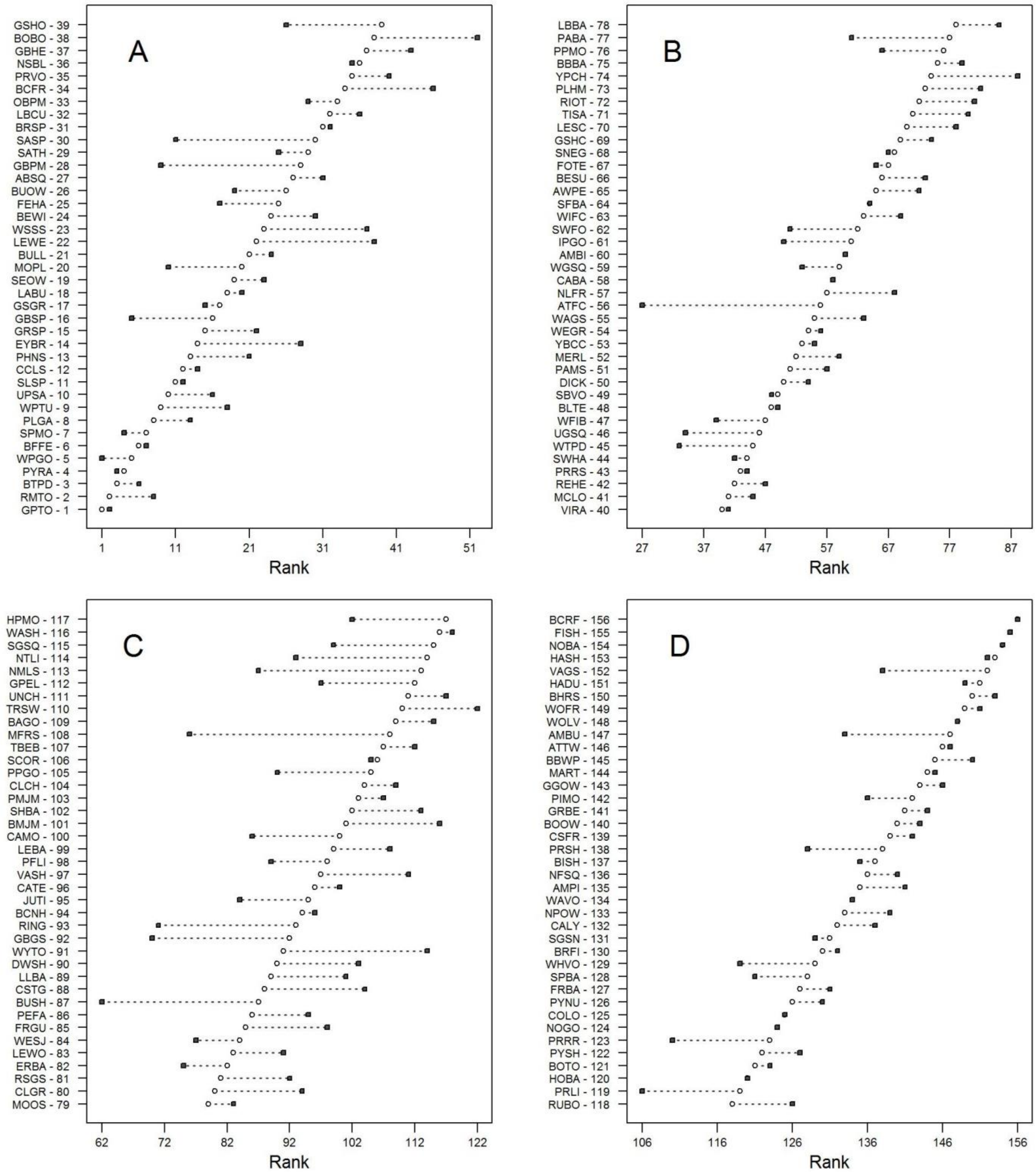


Figure B4. Range in exposure rank resulting from magnitude of buildout. Abscissa shows the exposure rank under the anticipated scenario (hollow circles) and unrestrained scenario (solid squares), where a rank of 1 is the most exposed to development. Ordinate shows individual species (see Table A1 for codes) ordered by their exposure under the anticipated scenario. Dotted lines represent the difference in rank between the scenarios. Panels A-D show different subsets of the 156 species analyzed.



Appendix C: Exposure values and confidence index calculations for Wyoming SGCN

Confidence Index Calculation

A Confidence Index was calculated for each species that represents the degree of confidence in the exposure estimate for that species. It was calculated using the same method developed for the model quality index of Chapter 1, which placed several well-supported validation statistics on a 0 to 1 scale and combined them using a simple weighted average (Equation C1).

$$\mathrm{CI} = \frac{\left(\frac{NOS+OQS}{2}\right)*0.75+\left(\frac{AUC+OES+ERS+BI}{4}\right)+EC}{2.75} \qquad \text{Equation C1}$$

The individual components of Equation C1 are as follows:

1. NOS (Number of Occurrences Score): More occurrences, or a larger sample size, lead to more robust models. NOS values of 1 reflect species with more than 100 occurrences; values of 0.75 reflect species with between 50 and 100 occurrences; values of 0.5 reflect species with between 20 and 50 occurrences; and values of 0 reflect species with less than 20 occurrences.
2. OQS (Occurrence Quality Score): All occurrences were scored based on their quality, as noted in the text and Table 1. These data were used to calculate average occurrence quality for the each model set. The resulting values were rescaled to range from 0 (very poor quality dataset) to 1 (very high quality dataset).
3. AUC (Area Under the Curve): We calculated the ROC AUC for each cross validation model based on a holdout dataset (Bradley 1997, Fielding and Bell 1997). A value of 0.5 indicates

model performance no better than chance, values below 0.5 indicate counter prediction, and values above 0.5 indicate increasingly strong classification to an upper limit of 1.

4. OES (Omission Error Score): Omission error is the proportion of test data miss-classified using the optimal binary threshold for each cross validation model, where higher values indicate lower quality models. OES was calculated by subtracting the omission error from one.
5. ERS (Expert Review Score): We scored the final model for each species using a simple categorical system reflecting how well local biologists felt it represented the species' true distribution in Wyoming. "High Quality" models were deemed to represent the species distribution well (ERS = 1). "Medium Quality" models represented the species distribution fairly well, but with minor errors of omission or commission (ERS = 0.5). "Low Quality" models were deemed to be either questionable or beyond our ability to accurately assess (ERS = 0).
6. BI (Boyce Index): The Boyce index is essentially a spearman rank correlation coefficient (rs) that varies between -1 (counter prediction) and 1 (positive prediction), with values statistically close to zero indicating that the model does not differ from a random model (Boyce et al. 2002). No model in this study had a negative Boyce Index, and values closer to 0 indicate poorer model fit.
7. EC (Exposure Change): We calculated the EI for each cross validation model of each species and assessed its level of variation by calculated the range of resulting values, divided the range by the minimum value, subtracted the result from one, and replaced negative values with zero. The resulting fraction ranged from 0 when the range of values of the cross-

validated exposure estimates was more than 100% of the minimum value (i.e., highly uncertain EI), to 1 when there was no variation in EI.

The first two components (number of occurrences and occurrence quality) were given slightly less weight than the others, because they are indirect measures of model quality. A model constructed using a small or low-quality sample is likely to be more uncertain, but is not definitively poor. It is nonetheless useful to incorporate them in addition to true validation statistics, because a model built on a small sample is more likely to be uncertain even if it validates well. For instance, a small sample size could indicate under-sampling of the environment for the species in question, and additional survey effort could place the species in substantially different environments.

Table C1. Exposure Index (EI) values for all 156 Wyoming Species of Greatest Conservation Need (SGCN) listed in order of decreasing 2030 total EI.

Exp. Rank	Species	Species Code	Total EI 1950	Total EI 1980	Total EI 2010	Total EI 2030	Oil & Gas EI 2030	Wind EI 2030	ΔEI 2010 to 2030
1	Great Plains Toad (Anaxyrus cognatus)	GPTO	0.005	0.036	0.182	0.278	0.277	<0.001	53%
2	Rocky Mountain Toad (Anaxyrus woodhousii woodhousii)	RMTO	0.006	0.030	0.143	0.210	0.209	<0.001	47%
3	Black-tailed Prairie Dog (Cynomys ludovicianus)	BTPD	0.005	0.034	0.136	0.205	0.201	0.004	51%
4	Pygmy Rabbit (Brachylagus idahoensis)	PYRA	0.003	0.025	0.098	0.201	0.198	0.004	105%
5	Wyoming Pocket Gopher (Thomomys clusius)	WPGO	0.002	0.024	0.112	0.196	0.188	0.009	75%
6	Black-footed Ferret (Mustela nigripes)	BFFE	<0.001	0.002	0.025	0.181	0.004	0.177	613%
7	Silky Pocket Mouse (Perognathus flavus)	SPMO	0.003	0.055	0.127	0.178	0.172	0.006	40%
8	Plains Gartersnake (Thamnophis radix)	PLGA	0.004	0.023	0.119	0.174	0.173	0.002	47%
9	Western Painted Turtle (Chrysemys picta bellii)	WPTU	0.006	0.024	0.112	0.165	0.163	0.001	48%
10	Upland Sandpiper (Bartramia longicauda)	UPSA	0.003	0.025	0.105	0.158	0.154	0.004	50%
11	Plains Spadefoot (Spea bombifrons)	SLSP	0.006	0.027	0.103	0.155	0.152	0.003	51%
12	Chestnut-collared Longspur (Calcarius ornatus)	CCLS	0.003	0.024	0.096	0.151	0.131	0.021	58%
13	Plains Hog-nosed Snake (Heterodon nasicus)	PHNS	0.006	0.025	0.100	0.150	0.147	0.003	51%
14	Eastern Yellow-bellied Racer (Coluber constrictor flaviventris)	EYBR	0.006	0.025	0.096	0.146	0.144	0.002	52%
15	Grasshopper Sparrow (Ammodramus savannarum)	GRSP	0.004	0.023	0.091	0.141	0.136	0.004	55%
16	Great Basin Spadefoot (Spea intermontana)	GBSP	0.002	0.020	0.083	0.136	0.135	<0.001	64%
17	Greater Sage-Grouse (Centrocercus urophasianus)	GSGR	0.004	0.022	0.080	0.135	0.125	0.010	69%
18	Lark Bunting (Calamospiza melanocorys)	LABU	0.004	0.021	0.081	0.134	0.125	0.009	64%
19	Short-eared Owl (Asio flammeus)	SEOW	0.005	0.022	0.083	0.133	0.128	0.004	59%

Exp. Rank	Species	Species Code	Total EI 1950	Total EI 1980	Total EI 2010	Total EI 2030	Oil & Gas EI 2030	Wind EI 2030	ΔEI 2010 to 2030
20	Mountain Plover (Charadrius montanus)	MOPL	0.003	0.018	0.074	0.133	0.119	0.014	80%
21	Bullsnake (Pituophis catenifer sayi)	BULL	0.006	0.024	0.084	0.132	0.128	0.004	56%
22	Least Weasel (Mustela nivalis)	LEWE	0.002	0.003	0.074	0.130	0.130	<0.001	75%
23	Western Spiny Softshell (Apalone spinifera hartwegi)	WSSS	0.005	0.020	0.087	0.126	0.123	0.003	46%
24	Bald Eagle; winter (Haliaeetus leucocephalus)	BEWI	0.004	0.020	0.077	0.125	0.119	0.005	62%
25	Ferruginous Hawk (Buteo regalis)	FEHA	0.003	0.018	0.069	0.123	0.112	0.011	78%
26	Burrowing Owl (Athene cunicularia)	BUOW	0.003	0.019	0.072	0.123	0.115	0.008	70%
27	Abert's Squirrel (Sciurus aberti)	ABSQ	<0.001	<0.001	<0.001	0.115	<0.001	0.115	>1000 %
28	Great Basin Pocket Mouse (Perognathus parvus)	GBPM	0.002	0.016	0.079	0.115	0.111	0.004	46%
29	Sage Thrasher (Oreoscoptes montanus)	SATH	0.004	0.017	0.062	0.113	0.102	0.011	83%
30	Sage Sparrow (Amphispiza belli)	SASP	0.003	0.016	0.059	0.112	0.103	0.009	92%
31	Brewer's Sparrow (Spizella breweri)	BRSP	0.003	0.017	0.062	0.110	0.101	0.009	77%
32	Long-billed Curlew (Numenius americanus)	LBCU	0.004	0.020	0.062	0.109	0.103	0.006	75%
33	Olive-backed Pocket Mouse (Perognathus fasciatus)	OBPM	0.004	0.017	0.063	0.108	0.097	0.011	71%
34	Boreal Chorus Frog (Pseudacris maculata)	BCFR	0.004	0.018	0.063	0.107	0.102	0.005	70%
35	Prairie Vole (Microtus ochrogaster)	PRVO	0.004	0.020	0.068	0.106	0.101	0.005	55%
36	Northern Sagebrush Lizard (Sceloporus graciosus graciosus)	NSBL	0.004	0.015	0.064	0.105	0.102	0.003	64%
37	Great Blue Heron (Ardea herodias)	GBHE	0.004	0.017	0.064	0.105	0.099	0.005	63%
38	Bobolink (Dolichonyx oryzivorus)	BOBO	0.002	0.011	0.059	0.100	0.096	0.004	70%
39	Greater Short-horned Lizard (Phrynosoma hernandesi)	GSHO	0.003	0.015	0.048	0.099	0.090	0.009	105%
40	Virginia Rail (Rallus limicola)	VIRA	0.003	0.015	0.056	0.099	0.089	0.009	78%

Exp. Rank	Species	Species Code	Total EI 1950	Total EI 1980	Total EI 2010	Total EI 2030	Oil & Gas EI 2030	Wind EI 2030	ΔEI 2010 to 2030
41	McCown's Longspur (Calcarius mccownii)	MCLO	0.003	0.015	0.055	0.095	0.072	0.022	71%
42	Redhead (Aythya americana)	REHE	0.005	0.019	0.055	0.094	0.086	0.008	71%
43	Prairie Rattlesnake (Crotalus viridis)	PRRS	0.004	0.015	0.053	0.094	0.079	0.015	78%
44	Swainson's Hawk (Buteo swainsoni)	SWHA	0.003	0.014	0.051	0.093	0.082	0.011	84%
45	White-tailed Prairie Dog (Cynomys leucurus)	WTPD	0.004	0.014	0.044	0.092	0.079	0.012	106%
46	Uinta Ground Squirrel (Spermophilus armatus)	UGSQ	0.001	0.010	0.033	0.090	0.087	0.003	176%
47	White-faced Ibis (Plegadis chihi)	WFIB	0.004	0.016	0.047	0.090	0.080	0.009	90%
48	Black Tern (Chlidonias niger)	BLTE	0.004	0.015	0.047	0.089	0.080	0.009	91%
49	Sagebrush Vole (Lemmiscus curtatus)	SBVO	0.003	0.013	0.047	0.089	0.074	0.015	87%
50	Dickcissel (Spiza americana)	DICK	0.002	0.010	0.056	0.089	0.087	0.001	59%
51	Pale Milksnake (Lampropeltis triangulum multistriata)	PAMS	0.018	0.040	0.062	0.087	0.083	0.004	40%
52	Merlin (Falco columbarius)	MERL	0.003	0.013	0.052	0.086	0.081	0.005	64%
53	Yellow-billed Cuckoo (Coccyzus americanus)	YBCC	0.002	0.002	0.029	0.081	0.081	<0.001	180%
54	Western Grebe (Aechmophorus occidentalis)	WEGR	0.004	0.014	0.044	0.078	0.075	0.004	79%
55	Wandering Gartersnake (Thamnophis elegans vagrans)	WAGS	0.003	0.010	0.041	0.076	0.068	0.008	85%
56	Ash-throated Flycatcher (Myiarchus cinerascens)	ATFC	0.002	0.011	0.048	0.075	0.069	0.006	56%
57	Northern Leopard Frog (Lithobates pipiens)	NLFR	0.004	0.014	0.045	0.074	0.069	0.005	67%
58	Canvasback (Aythya valisineria)	CABA	0.004	0.013	0.041	0.074	0.060	0.014	82%
59	Wyoming Ground Squirrel (Spermophilus elegans)	WGSQ	0.002	0.008	0.028	0.073	0.049	0.025	163%
60	American Bittern (Botaurus lentiginosus)	AMBI	0.003	0.012	0.037	0.071	0.064	0.007	93%

Exp. Rank	Species	Species Code	Total EI 1950	Total EI 1980	Total EI 2010	Total EI 2030	Oil & Gas EI 2030	Wind EI 2030	ΔEI 2010 to 2030
61	Idaho Pocket Gopher (Thomomys idahoensis)	IPGO	<0.001	0.004	0.026	0.071	0.041	0.030	173%
62	Swift Fox (Vulpes velox)	SWFO	0.002	0.011	0.040	0.071	0.049	0.022	78%
63	Willow Flycatcher (Empidonax traillii)	WIFC	0.002	0.010	0.039	0.069	0.065	0.004	79%
64	Western Small-footed Myotis (Myotis ciliolabrum)	SFBA	0.005	0.016	0.041	0.069	0.065	0.004	67%
65	American White Pelican (Pelecanus erythrorhynchos)	AWPE	0.003	0.010	0.036	0.067	0.055	0.012	86%
66	Bald Eagle; summer (Haliaeetus leucocephalus)	BESU	0.002	0.010	0.035	0.066	0.061	0.005	87%
67	Forster's Tern (Sterna forsteri)	FOTE	0.003	0.011	0.027	0.065	0.055	0.011	142%
68	Snowy Egret (Egretta thula)	SNEG	0.002	0.007	0.019	0.064	0.043	0.021	241%
69	Greater Sandhill Crane (Grus canadensis)	GSHC	0.002	0.011	0.033	0.063	0.059	0.005	89%
70	Lesser Scaup (Aythya affinis)	LESC	0.002	0.009	0.032	0.060	0.050	0.010	89%
71	Tiger Salamander (Ambystoma mavortium)	TISA	0.002	0.010	0.031	0.059	0.055	0.005	91%
72	River Otter (Lontra canadensis)	RIOT	0.001	0.008	0.025	0.059	0.055	0.003	138%
73	Plains Harvest Mouse (Reithrodontomys montanus)	PLHM	0.002	0.013	0.044	0.058	0.054	0.005	34%
74	Yellow-pine Chipmunk (Neotamias amoenus)	YPCH	<0.001	0.006	0.014	0.058	0.058	<0.001	301%
75	Big Brown Bat (Eptesicus fuscus)	BBBA	0.003	0.013	0.033	0.058	0.052	0.005	75%
76	Plains Pocket Mouse (Perognathus flavescens)	PPMO	<0.001	0.008	0.031	0.053	0.038	0.014	71%
77	Pallid Bat (Antrozous pallidus)	PABA	0.005	0.017	0.034	0.052	0.050	0.003	56%
78	Little Brown Myotis (Myotis lucifugus)	LBBA	0.004	0.013	0.029	0.052	0.045	0.007	82%
79	Moose (Alces alces)	MOOS	0.001	0.007	0.021	0.050	0.047	0.003	140%
80	Clark's Grebe (Aechmophorus clarkii)	CLGR	0.003	0.007	0.023	0.047	0.043	0.004	107%

Exp. Rank	Species	Species Code	Total EI 1950	Total EI 1980	Total EI 2010	Total EI 2030	Oil & Gas EI 2030	Wind EI 2030	ΔEI 2010 to 2030
81	Red-sided Gartersnake (Thamnophis sirtalis parietalis)	RSGS	0.004	0.011	0.030	0.047	0.045	0.002	55%
82	Eastern Red Bat (Lasiurus borealis)	ERBA	0.002	0.013	0.028	0.047	0.032	0.015	67%
83	Lewis' Woodpecker (Melanerpes lewis)	LEWO	0.002	0.009	0.027	0.046	0.042	0.004	73%
84	Western Scrub-Jay (Aphelocoma californica)	WESJ	0.001	0.006	0.022	0.041	0.035	0.006	86%
85	Franklin's Gull (Larus pipixcan)	FRGU	0.002	0.006	0.022	0.041	0.036	0.005	85%
86	Peregrine Falcon (Falco peregrinus)	PEFA	0.002	0.007	0.021	0.041	0.036	0.004	96%
87	Bushtit (Psaltriparus minimus)	BUSH	0.002	0.010	0.033	0.041	0.035	0.005	23%
88	Columbian Sharp-tailed Grouse (Tympanuchus phasianellus columbianus)	CSTG	0.002	0.004	0.024	0.037	0.036	0.002	56%
89	Long-legged Myotis (Myotis volans)	LLBA	0.002	0.008	0.021	0.035	0.032	0.003	68%
90	Dwarf Shrew (Sorex nanus)	DWSH	0.001	0.005	0.018	0.035	0.029	0.005	89%
91	Wyoming Toad (Anaxyrus baxteri)	WYTO	0.007	0.008	0.011	0.034	0.009	0.026	216%
92	Great Basin Gophersnake (Pituophis catenifer deserticola)	GBGS	0.001	0.008	0.024	0.033	0.029	0.004	36%
93	Ringtail (Bassariscus astutus)	RING	0.003	0.009	0.024	0.032	0.022	0.010	34%
94	Black-crowned Night-Heron (Nycticorax nycticorax)	BCNH	0.002	0.005	0.014	0.031	0.018	0.013	130%
95	Juniper Titmouse (Baeolophus ridgwayi)	JUTI	<0.001	0.004	0.011	0.031	0.018	0.012	179%
96	Caspian Tern (Sterna caspia)	CATE	<0.001	0.003	0.007	0.029	0.028	0.001	313%
97	Vagrant Shrew (Sorex vagrans)	VASH	0.001	0.004	0.015	0.028	0.026	0.003	86%
98	Plateau Fence Lizard (Sceloporus tristichus)	PFLI	<0.001	0.005	0.018	0.027	0.022	0.006	57%
99	Long-eared Myotis (Myotis evotis)	LEBA	0.001	0.006	0.013	0.026	0.023	0.003	101%

Exp. Rank	Species	Species Code	Total EI 1950	Total EI 1980	Total EI 2010	Total EI 2030	Oil & Gas EI 2030	Wind EI 2030	ΔEI 2010 to 2030
100	Canyon Mouse (Peromyscus crinitus)	CAMO	<0.001	0.005	0.013	0.023	0.015	0.008	74%
101	Bear Lodge Meadow Jumping Mouse (Zapus hudsonius campestris)	BMJM	<0.001	0.002	0.014	0.023	0.023	<0.001	61%
102	Silver-haired Bat (Lasionycteris noctivagans)	SHBA	0.002	0.005	0.010	0.021	0.016	0.005	115%
103	Preble's Meadow Jumping Mouse (Zapus hudsonius preblei)	PMJM	<0.001	0.002	0.003	0.021	0.003	0.018	534%
104	Cliff Chipmunk (Neotamias dorsalis)	CLCH	0.001	0.006	0.017	0.020	0.016	0.005	18%
105	Plains Pocket Gopher (Geomys bursarius)	PPGO	0.001	0.007	0.013	0.020	0.016	0.004	49%
106	Scott's Oriole (Icterus parisorum)	SCOR	0.001	0.006	0.017	0.020	0.018	0.001	16%
107	Townsend's Big-eared Bat (Corynorhinus townsendii)	TBEB	0.003	0.008	0.012	0.019	0.017	0.002	59%
108	Midget Faded Rattlesnake (Crotalus oreganus concolor)	MFRS	<0.001	0.004	0.015	0.019	0.017	0.001	27%
109	Barrow's Goldeneye (Bucephala islandica)	BAGO	0.001	0.005	0.009	0.019	0.018	<0.001	97%
110	Trumpeter Swan (Cygnus buccinator)	TRSW	<0.001	<0.001	0.005	0.017	0.017	<0.001	246%
111	Unita Chipmunk (Neotamias umbrinus)	UNCH	<0.001	0.003	0.006	0.016	0.012	0.004	173%
112	Great Plains Earless Lizard (Holbrookia maculata)	GPEL	<0.001	0.002	0.008	0.015	0.007	0.008	82%
113	Northern Many-lined Skink (Eumeces multivirgatus)	NMLS	<0.001	0.001	0.006	0.015	0.006	0.008	128%
114	Northern Tree Lizard (Urosaurus ornatus wrighti)	NTLI	0.001	0.005	0.012	0.015	0.012	0.003	26%
115	Spotted Ground Squirrel (Spermophilus spilosoma)	SGSQ	<0.001	0.001	0.003	0.013	0.003	0.010	358%
116	Water Shrew (Sorex palustris)	WASH	<0.001	0.002	0.005	0.013	0.008	0.005	158%
117	Hispid Pocket Mouse (Chaetodipus hispidus)	HPMO	<0.001	0.003	0.006	0.013	0.007	0.006	98%
118	Rubber Boa (Charina bottae)	RUBO	<0.001	0.003	0.005	0.012	0.012	<0.001	154%
119	Prairie Lizard (Sceloporus consobrinus)	PRLI	<0.001	<0.001	0.003	0.012	0.003	0.010	328%

Exp. Rank	Species	Species Code	Total EI 1950	Total EI 1980	Total EI 2010	Total EI 2030	Oil & Gas EI 2030	Wind EI 2030	ΔEI 2010 to 2030
120	Hoary Bat (Lasiurus cinereus)	HOBA	0.002	0.005	0.007	0.011	0.010	0.001	56%
121	Boreal Toad (Anaxyrus boreas boreas)	BOTO	<0.001	0.002	0.004	0.011	0.011	<0.001	198%
122	Pygmy Shrew (Sorex hoyi)	PYSH	<0.001	0.001	0.003	0.011	0.001	0.010	290%
123	Prairie Racerunner (Aspidoscelis sexlineatus viridis)	PRRR	<0.001	<0.001	<0.001	0.010	<0.001	0.009	>1000%
124	Northern Goshawk (Accipiter gentilis)	NOGO	<0.001	0.002	0.004	0.009	0.007	0.002	106%
125	Common Loon (Gavia immer)	COLO	<0.001	0.001	0.003	0.008	0.007	0.001	151%
126	Pygmy Nuthatch (Sitta pygmaea)	PYNU	<0.001	0.001	0.004	0.008	0.006	0.002	80%
127	Fringed Myotis (Myotis thysanodes)	FRBA	0.001	0.003	0.004	0.007	0.006	<0.001	47%
128	Spotted Bat (Euderma maculatum)	SPBA	<0.001	0.004	0.006	0.007	0.007	<0.001	18%
129	Western Heather Vole (Phenacomys intermedius)	WHVO	<0.001	<0.001	0.005	0.006	0.005	0.001	16%
130	Black Rosy-Finch (Leucosticte atrata)	BRFI	<0.001	0.002	0.003	0.006	0.005	0.001	91%
131	Smooth Green Snake (Opheodrys vernalis)	SGSN	<0.001	<0.001	0.001	0.006	0.001	0.005	446%
132	Canada Lynx (Lynx canadensis)	CALY	<0.001	0.001	0.002	0.005	0.005	<0.001	122%
133	Northern Pygmy-Owl (Glaucidium gnoma)	NPOW	<0.001	<0.001	0.001	0.004	0.004	<0.001	215%
134	Water Vole (Microtus richardsoni)	WAVO	<0.001	<0.001	0.002	0.004	0.004	<0.001	93%
135	American Pika (Ochotona princeps)	AMPI	<0.001	0.001	0.002	0.004	0.004	<0.001	60%
136	Northern Flying Squirrel (Glaucomys sabrinus)	NFSQ	<0.001	<0.001	0.002	0.003	0.003	<0.001	103%
137	Bighorn Sheep (Ovis canadensis)	BISH	<0.001	0.002	0.002	0.003	0.003	<0.001	42%
138	Preble's Shrew (Sorex preblei)	PRSH	<0.001	0.001	0.003	0.003	0.003	<0.001	11%
139	Columbia Spotted Frog (Rana luteiventris)	CSFR	<0.001	<0.001	<0.001	0.003	0.003	<0.001	592%
140	Boreal Owl (Aegolius funereus)	BOOW	<0.001	<0.001	0.001	0.002	0.002	<0.001	87%

Exp. Rank	Species	Species Code	Total EI 1950	Total EI 1980	Total EI 2010	Total EI 2030	Oil & Gas EI 2030	Wind EI 2030	ΔEI 2010 to 2030
141	Grizzly Bear (Ursus arctos)	GRBE	<0.001	<0.001	0.001	0.002	0.002	<0.001	63%
142	Pinyon Mouse (Peromyscus truei)	PIMO	<0.001	<0.001	0.001	0.001	<0.001	<0.001	27%
143	Great Gray Owl (Strix nebulosa)	GGOW	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	212%
144	Marten (Martes americana)	MART	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	53%
145	Black-backed Woodpecker (Picoides arcticus)	BBWP	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	22%
146	American Three-toed Woodpecker (Picoides dorsalis)	ATTW	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	80%
147	American Bullfrog (Lithobates catesbieanus)	AMBU	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	>1000 %
148	Wolverine (Gulo gulo)	WOLV	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	215%
149	Wood Frog (Lithobates sylvaticus)	WOFR	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	157%
150	Black Hills Redbelly Snake (Storeria occipitomaculata pahasapae)	BHRS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	10%
151	Harlequin Duck (Histrionicus histrionicus)	HADU	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	31%
152	Valley Gartersnake (Thamnophis sirtalis fitchi)	VAGS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	113%
153	Hayden's Shrew (Sorex haydeni)	HASH	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	184%
154	Northern Myotis (Myotis septentrionalis)	NOBA	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	1%
155	Fisher (Martes pennanti)	FISH	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0%
156	Brown-capped Rosy Finch (Leucosticte australis)	BCRF	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	>1000 %

Table C2. Model validation statistics confidence index (CI) for all 156 species in this study. Species codes are given in Table BBB1. Values following '±' are standard deviations. Numbers in parenthesis indicate the transformation of each value into an uncertainty score on a scale of 0 (low uncertainty) to 1 (high uncertainty), where such transformation was necessary.

Taxonomic Class	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Boyce Index (BI)	Exposure Change; (EC)	CI
Amphibian	TISA	228 (1)	9.55 ± 2.94 (0.69)	0.71 ± 0.04	0.35 ± 0.12 (0.65)	Low (0)	0.85 ± 0.11	0.97	0.79
Amphibian	BOTO	256 (1)	8.97 ± 3 (0.62)	0.91 ± 0.02	0.03 ± 0.03 (0.97)	High (1)	0.76 ± 0.13	0.8	0.84
Amphibian	GPTO	20 (0.5)	9.65 ± 2.83 (0.71)	0.95 ± 0.05	0.15 ± 0.24 (0.85)	Medium (0.5)	na	0.91	0.71
Amphibian	RMTO	106 (1)	10.36 ± 2.87 (0.79)	0.91 ± 0.03	0.14 ± 0.1 (0.86)	Medium (0.5)	0.82 ± 0.27	0.84	0.83
Amphibian	WYTO	10 (0)	6.1 ± 2.56 (0.26)	0.99 ± 0.02	0.2 ± 0.42 (0.8)	Medium (0.5)	na	0.88	0.57
Amphibian	BCFR	97 (0.75)	7.88 ± 2.78 (0.48)	0.7 ± 0.06	0.42 ± 0.19 (0.58)	Low (0)	0.62 ± 0.32	0.9	0.67
Amphibian	SLSP	37 (0.5)	7.84 ± 2.73 (0.48)	0.77 ± 0.09	0.29 ± 0.15 (0.71)	Low (0)	na	0.93	0.61
Amphibian	GBSP	27 (0.5)	7.96 ± 2.36 (0.5)	0.88 ± 0.07	0.12 ± 0.19 (0.88)	Medium (0.5)	na	0.96	0.69
Amphibian	AMBU	3 (0)	4.67 ± 0.58 (0.08)	0.3 ± 0.48	0.67 ± 0.58 (0.33)	Low (0)	na	0	0.07
Amphibian	NLFR	225 (1)	9.8 ± 2.84 (0.72)	0.81 ± 0.06	0.29 ± 0.13 (0.71)	Medium (0.5)	0.96 ± 0.07	0.9	0.83
Amphibian	WOFR	62 (0.75)	10.32 ± 2.02 (0.79)	0.98 ± 0.02	0.05 ± 0.08 (0.95)	Medium (0.5)	0.78 ± 0.23	0.01	0.51
Amphibian	CSFR	291 (1)	10.33 ± 2.26 (0.79)	0.94 ± 0.01	0.02 ± 0.01 (0.98)	Medium (0.5)	0.67 ± 0.3	0.52	0.71
Bird	COLO	98 (0.75)	6.42 ± 2.21 (0.3)	0.95 ± 0.02	0.13 ± 0.14 (0.87)	Medium (0.5)	0.66 ± 0.37	0.74	0.68
Bird	WEGR	144 (1)	5.29 ± 1.38 (0.16)	0.87 ± 0.03	0.2 ± 0.1 (0.8)	Low (0)	0.82 ± 0.13	0.84	0.69
Bird	CLGR	29 (0.5)	6.45 ± 2.13 (0.31)	0.88 ± 0.12	0.28 ± 0.31 (0.72)	Low (0)	na	0.76	0.53
Bird	AWPE	430 (1)	6.41 ± 1.89 (0.3)	0.82 ± 0.04	0.22 ± 0.06 (0.78)	Medium (0.5)	0.93 ± 0.13	0.83	0.76
Bird	AMBI	60 (0.75)	5.45 ± 1.68 (0.18)	0.65 ± 0.12	0.47 ± 0.23 (0.53)	Medium (0.5)	0.75 ± 0.27	0.83	0.65
Bird	GBHE	847 (1)	5.65 ± 1.32 (0.21)	0.69 ± 0.02	0.33 ± 0.04 (0.67)	Medium (0.5)	0.97 ± 0.05	0.96	0.77
Bird	SNEG	43 (0.5)	5.3 ± 1.47 (0.16)	0.91 ± 0.04	0.17 ± 0.17 (0.84)	Medium (0.5)	0.95 ± 0.07	0.84	0.69
Bird	BCNH	76 (0.75)	5.93 ± 1.8 (0.24)	0.88 ± 0.06	0.12 ± 0.1 (0.88)	Medium (0.5)	0.67 ± 0.38	0.89	0.73
Bird	WFIB	89 (0.75)	5.97 ± 2.03 (0.25)	0.74 ± 0.06	0.36 ± 0.19 (0.64)	Medium (0.5)	0.9 ± 0.12	0.9	0.72

Taxonomic Class	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Boyce Index (BI)	Exposure Change; (EC)	CI
Bird	TRSW	165 (1)	6.67 ± 2.06 (0.33)	0.95 ± 0.01	0.09 ± 0.09 (0.91)	Medium (0.5)	0.34 ± 0.13	0.66	0.67
Bird	CABA	62 (0.75)	5.66 ± 1.33 (0.21)	0.73 ± 0.09	0.36 ± 0.25 (0.64)	Low (0)	0.63 ± 0.32	0.86	0.63
Bird	REHE	99 (0.75)	5.69 ± 1.72 (0.21)	0.76 ± 0.06	0.18 ± 0.1 (0.82)	Medium (0.5)	0.73 ± 0.28	0.89	0.71
Bird	LESC	102 (1)	5.43 ± 1.35 (0.18)	0.64 ± 0.1	0.36 ± 0.15 (0.64)	Low (0)	0.43 ± 0.37	0.9	0.65
Bird	HADU	47 (0.5)	6.45 ± 2.06 (0.31)	0.94 ± 0.06	0.14 ± 0.19 (0.86)	Medium (0.5)	0.56 ± 0.45	0.14	0.42
Bird	BAGO	61 (0.75)	5.46 ± 1.4 (0.18)	0.87 ± 0.04	0.23 ± 0.21 (0.77)	Medium (0.5)	0.5 ± 0.34	0.76	0.64
Bird	BESU	353 (1)	6.36 ± 1.93 (0.29)	0.72 ± 0.04	0.34 ± 0.13 (0.66)	High (1)	0.92 ± 0.09	0.92	0.81
Bird	BEWI	2794 (1)	5.49 ± 1.53 (0.19)	0.69 ± 0.01	0.32 ± 0.04 (0.68)	Medium (0.5)	0.9 ± 0.08	0.98	0.77
Bird	NOGO	421 (1)	6.58 ± 2.41 (0.32)	0.89 ± 0.02	0.17 ± 0.06 (0.83)	High (1)	0.92 ± 0.1	0.91	0.84
Bird	SWHA	861 (1)	5.64 ± 1.6 (0.2)	0.69 ± 0.02	0.35 ± 0.09 (0.65)	Medium (0.5)	0.94 ± 0.05	0.98	0.77
Bird	FEHA	1443 (1)	6.12 ± 1.92 (0.26)	0.74 ± 0.02	0.24 ± 0.1 (0.76)	Medium (0.5)	1 ± 0	0.98	0.8
Bird	MERL	182 (1)	6.35 ± 2.28 (0.29)	0.63 ± 0.07	0.64 ± 0.15 (0.36)	Medium (0.5)	0.6 ± 0.29	0.95	0.71
Bird	PEFA	181 (1)	7.39 ± 2.58 (0.42)	0.68 ± 0.05	0.37 ± 0.1 (0.63)	Medium (0.5)	0.81 ± 0.17	0.88	0.75
Bird	GSGR	1610 (1)	7.87 ± 1.48 (0.48)	0.86 ± 0.01	0.09 ± 0.03 (0.91)	Medium (0.5)	0.88 ± 0.14	0.97	0.84
Bird	CSTG	40 (0.5)	8.38 ± 2.82 (0.55)	0.98 ± 0.03	0.13 ± 0.18 (0.88)	High (1)	0.98 ± 0.06	0.58	0.7
Bird	VIRA	16 (0)	6.31 ± 1.54 (0.29)	0.76 ± 0.16	0.45 ± 0.37 (0.55)	Low (0)	1 ± 0	0.93	0.59
Bird	GSHC	1181 (1)	6.54 ± 1.88 (0.32)	0.75 ± 0.02	0.25 ± 0.03 (0.75)	Low (0)	0.97 ± 0.05	0.9	0.73
Bird	MOPL	302 (1)	8.63 ± 2.91 (0.58)	0.81 ± 0.04	0.23 ± 0.12 (0.77)	High (1)	0.9 ± 0.12	0.95	0.88
Bird	UPSA	120 (1)	6.08 ± 1.66 (0.26)	0.92 ± 0.02	0.11 ± 0.14 (0.89)	Medium (0.5)	0.78 ± 0.24	0.4	0.6
Bird	LBCU	341 (1)	6.17 ± 1.77 (0.27)	0.74 ± 0.05	0.35 ± 0.09 (0.65)	Medium (0.5)	1 ± 0	0.94	0.78
Bird	FRGU	33 (0.5)	4.97 ± 1.33 (0.12)	0.86 ± 0.08	0.29 ± 0.3 (0.71)	Medium (0.5)	na	0.49	0.45
Bird	CATE	33 (0.5)	5.91 ± 2.1 (0.24)	0.92 ± 0.07	0.17 ± 0.22 (0.83)	Medium (0.5)	na	0.46	0.47
Bird	FOTE	35 (0.5)	6.51 ± 2.13 (0.31)	0.85 ± 0.13	0.28 ± 0.27 (0.73)	Medium (0.5)	na	0.85	0.61
Bird	BLTE	42 (0.5)	5.33 ± 1.48 (0.17)	0.83 ± 0.1	0.17 ± 0.19 (0.84)	Low (0)	0.93 ± 0.09	0.94	0.67
Bird	YBCC	19 (0)	6.79 ± 2.18 (0.35)	0.94 ± 0.04	0.25 ± 0.35 (0.75)	Low (0)	na	0.7	0.45

Taxonomic Class	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Boyce Index (BI)	Exposure Change; (EC)	CI
Bird	NPOW	11 (0)	7 ± 1.41 (0.38)	0.95 ± 0.05	0.1 ± 0.32 (0.9)	Medium (0.5)	na	0	0.26
Bird	BUOW	655 (1)	6.9 ± 2.41 (0.36)	0.78 ± 0.02	0.22 ± 0.05 (0.78)	High (1)	0.93 ± 0.07	0.97	0.86
Bird	GGOW	55 (0.75)	6.07 ± 1.74 (0.26)	0.92 ± 0.05	0.11 ± 0.16 (0.89)	High (1)	0.54 ± 0.3	0.69	0.69
Bird	SEOW	142 (1)	6.26 ± 1.81 (0.28)	0.73 ± 0.05	0.35 ± 0.1 (0.65)	Medium (0.5)	0.74 ± 0.25	0.96	0.76
Bird	BOOW	58 (0.75)	9.36 ± 1.98 (0.67)	0.94 ± 0.03	0.05 ± 0.11 (0.95)	High (1)	0.43 ± 0.37	0.65	0.73
Bird	LEWO	118 (1)	5.84 ± 1.55 (0.23)	0.88 ± 0.06	0.24 ± 0.12 (0.76)	Medium (0.5)	0.85 ± 0.16	0.83	0.74
Bird	BBWP	11 (0)	7.73 ± 2.69 (0.47)	0.95 ± 0.07	0.1 ± 0.32 (0.9)	Medium (0.5)	na	0.67	0.52
Bird	ATTW	110 (1)	9.94 ± 2.72 (0.74)	0.95 ± 0.02	0.09 ± 0.14 (0.91)	High (1)	0.75 ± 0.31	0.74	0.84
Bird	WIFC	95 (0.75)	6.24 ± 1.91 (0.28)	0.68 ± 0.08	0.45 ± 0.18 (0.55)	Low (0)	0.59 ± 0.24	0.92	0.64
Bird	ATFC	60 (0.75)	6.55 ± 2.73 (0.32)	0.9 ± 0.04	0.18 ± 0.17 (0.82)	Medium (0.5)	0.82 ± 0.16	0.88	0.74
Bird	WESJ	26 (0.5)	7.42 ± 2.8 (0.43)	0.97 ± 0.04	0.12 ± 0.19 (0.88)	Medium (0.5)	na	0.75	0.61
Bird	JUTI	31 (0.5)	8.48 ± 3.03 (0.56)	0.97 ± 0.03	0.15 ± 0.25 (0.85)	Medium (0.5)	na	0.71	0.61
Bird	BUSH	24 (0.5)	8.33 ± 3.67 (0.54)	0.91 ± 0.07	0.1 ± 0.21 (0.9)	Medium (0.5)	na	0.9	0.68
Bird	PYNU	35 (0.5)	6.63 ± 2.66 (0.33)	0.94 ± 0.07	0.13 ± 0.19 (0.87)	Medium (0.5)	na	0.19	0.39
Bird	SATH	635 (1)	8.95 ± 2.5 (0.62)	0.69 ± 0.03	0.19 ± 0.07 (0.81)	High (1)	0.69 ± 0.24	0.97	0.86
Bird	DICK	24 (0.5)	7.67 ± 2.32 (0.46)	0.95 ± 0.05	0 ± 0 (1)	Medium (0.5)	na	0.57	0.56
Bird	BRSP	1372 (1)	8.8 ± 2.54 (0.6)	0.65 ± 0.02	0.26 ± 0.05 (0.74)	High (1)	0.82 ± 0.2	0.98	0.87
Bird	SASP	631 (1)	8.21 ± 2.83 (0.53)	0.78 ± 0.02	0.19 ± 0.06 (0.81)	High (1)	0.88 ± 0.13	0.98	0.88
Bird	LABU	407 (1)	6.02 ± 1.5 (0.25)	0.71 ± 0.02	0.28 ± 0.14 (0.72)	High (1)	0.71 ± 0.28	0.96	0.81
Bird	GRSP	261 (1)	7.79 ± 1.75 (0.47)	0.82 ± 0.03	0.26 ± 0.06 (0.74)	High (1)	0.82 ± 0.28	0.92	0.84
Bird	MCLO	152 (1)	8.24 ± 2.63 (0.53)	0.9 ± 0.03	0.17 ± 0.11 (0.83)	High (1)	0.84 ± 0.15	0.85	0.84
Bird	CCLS	90 (0.75)	7.38 ± 2.31 (0.42)	0.89 ± 0.05	0.22 ± 0.19 (0.78)	High (1)	0.9 ± 0.09	0.83	0.79
Bird	BOBO	46 (0.5)	6.72 ± 1.8 (0.34)	0.83 ± 0.11	0.27 ± 0.23 (0.74)	Medium (0.5)	0.84 ± 0.22	0.67	0.62
Bird	SCOR	9 (0)	6.56 ± 3.21 (0.32)	0.88 ± 0.31	0.22 ± 0.44 (0.78)	Medium (0.5)	na	0.63	0.47
Bird	BRFI	7 (0)	7.86 ± 2.19 (0.48)	0.65 ± 0.46	0.29 ± 0.49 (0.71)	Low (0)	na	0	0.19

Taxonomic Class	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Boyce Index (BI)	Exposure Change; (EC)	CI
Bird	BCRF	2 (0)	9 ± 2.83 (0.63)	0.15 ± 0.34	0.5 ± 0.71 (0.5)	Low (0)	na	1	0.51
Mammal	PRSH	3 (0)	4.33 ± 3.51 (0.04)	0.3 ± 0.48	1 ± 0 (0)	Low (0)	na	0.28	0.14
Mammal	VASH	22 (0.5)	4.86 ± 1.04 (0.11)	0.82 ± 0.18	0.33 ± 0.33 (0.67)	Low (0)	na	0.55	0.42
Mammal	DWSH	15 (0)	5.8 ± 1.7 (0.23)	0.75 ± 0.27	0.5 ± 0.47 (0.5)	Medium (0.5)	na	0.41	0.34
Mammal	WASH	23 (0.5)	5.22 ± 1.31 (0.15)	0.85 ± 0.07	0.18 ± 0.24 (0.82)	Medium (0.5)	na	0.86	0.6
Mammal	PYSH	5 (0)	5.8 ± 1.64 (0.23)	0.5 ± 0.52	0.2 ± 0.45 (0.8)	Low (0)	na	0.93	0.49
Mammal	HASH	14 (0)	6.21 ± 2.26 (0.28)	0.97 ± 0.04	0.05 ± 0.16 (0.95)	Medium (0.5)	na	0	0.26
Mammal	LBBA	119 (1)	7.18 ± 3.54 (0.4)	0.75 ± 0.05	0.29 ± 0.14 (0.71)	Medium (0.5)	0.78 ± 0.16	0.87	0.76
Mammal	LEBA	60 (0.75)	7.55 ± 3.15 (0.44)	0.8 ± 0.1	0.28 ± 0.24 (0.72)	Medium (0.5)	0.69 ± 0.33	0.8	0.7
Mammal	FRBA	24 (0.5)	10.25 ± 2.36 (0.78)	0.94 ± 0.03	0.12 ± 0.19 (0.88)	Medium (0.5)	na	0.69	0.64
Mammal	LLBA	80 (0.75)	8.51 ± 3.26 (0.56)	0.8 ± 0.11	0.35 ± 0.23 (0.65)	Medium (0.5)	0.82 ± 0.23	0	0.43
Mammal	SFBA	66 (0.75)	7.39 ± 2.58 (0.42)	0.8 ± 0.08	0.32 ± 0.18 (0.68)	Medium (0.5)	0.75 ± 0.31	0	0.41
Mammal	NOBA	3 (0)	8.67 ± 2.89 (0.58)	0.28 ± 0.45	0 ± 0 (1)	Low (0)	na	0	0.2
Mammal	SHBA	63 (0.75)	7.92 ± 3.57 (0.49)	0.8 ± 0.08	0.27 ± 0.17 (0.73)	Medium (0.5)	0.88 ± 0.18	0.79	0.72
Mammal	BBBA	83 (0.75)	6.94 ± 3.37 (0.37)	0.74 ± 0.07	0.26 ± 0.15 (0.74)	Medium (0.5)	0.67 ± 0.32	0.85	0.7
Mammal	ERBA	5 (0)	5.4 ± 1.67 (0.18)	0.37 ± 0.41	0 ± 0 (1)	Low (0)	na	0.56	0.35
Mammal	HOBA	63 (0.75)	8.81 ± 3.23 (0.6)	0.83 ± 0.06	0.24 ± 0.08 (0.76)	Medium (0.5)	0.82 ± 0.26	0.56	0.65
Mammal	SPBA	14 (0)	9.57 ± 2.14 (0.7)	0.98 ± 0.03	0.2 ± 0.42 (0.8)	Medium (0.5)	na	0.65	0.54
Mammal	TBEB	50 (0.75)	7.92 ± 1.95 (0.49)	0.9 ± 0.1	0.16 ± 0.16 (0.84)	Medium (0.5)	0.84 ± 0.22	0.53	0.64
Mammal	PABA	16 (0)	7.38 ± 2.5 (0.42)	0.79 ± 0.24	0.3 ± 0.48 (0.7)	Medium (0.5)	na	0.65	0.48
Mammal	AMPI	170 (1)	6.08 ± 1.97 (0.26)	0.96 ± 0.02	0.11 ± 0.08 (0.89)	High (1)	0.65 ± 0.25	0.74	0.76
Mammal	PYRA	278 (1)	10.39 ± 2.4 (0.8)	0.93 ± 0.01	0.09 ± 0.07 (0.91)	High (1)	0.86 ± 0.14	0.93	0.92
Mammal	YPCH	12 (0)	4.25 ± 2.22 (0.03)	0.89 ± 0.09	0.35 ± 0.47 (0.65)	Medium (0.5)	na	0.44	0.35
Mammal	CLCH	8 (0)	6.25 ± 1.39 (0.28)	0.79 ± 0.42	0.13 ± 0.35 (0.88)	Low (0)	na	0.94	0.53
Mammal	UNCH	16 (0)	4.25 ± 2.27 (0.03)	0.84 ± 0.16	0.06 ± 0.02 (0.94)	Medium (0.5)	na	0.8	0.5

Taxonomic Class	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Boyce Index (BI)	Exposure Change; (EC)	CI
Mammal	UGSQ	67 (0.75)	6.88 ± 3.14 (0.36)	0.88 ± 0.03	0.2 ± 0.1 (0.8)	Low (0)	0.47 ± 0.3	0.74	0.61
Mammal	SGSQ	13 (0)	5.46 ± 2.07 (0.18)	0.91 ± 0.18	0.45 ± 0.38 (0.55)	Medium (0.5)	na	0.83	0.51
Mammal	WGSQ	268 (1)	6.13 ± 2.16 (0.27)	0.82 ± 0.04	0.17 ± 0.1 (0.83)	Low (0)	0.48 ± 0.34	0.91	0.7
Mammal	BTPD	1132 (1)	12 ± 0 (1)	0.88 ± 0.01	0.03 ± 0.01 (0.97)	High (1)	0.18 ± 0.18	0.97	0.9
Mammal	WTPD	1175 (1)	6.1 ± 2.05 (0.26)	0.8 ± 0.01	0.06 ± 0.03 (0.94)	High (1)	0.07 ± 0.09	0.97	0.78
Mammal	ABSQ	4 (0)	5.25 ± 1.5 (0.16)	0.4 ± 0.52	0.25 ± 0.5 (0.75)	Medium (0.5)	na	1	0.53
Mammal	NFSQ	21 (0.5)	5.57 ± 1.5 (0.2)	0.92 ± 0.06	0.27 ± 0.44 (0.73)	Medium (0.5)	na	0.52	0.48
Mammal	WPGO	15 (0)	8.47 ± 3.52 (0.56)	0.97 ± 0.04	0.2 ± 0.42 (0.8)	Medium (0.5)	na	0.86	0.59
Mammal	IPGO	27 (0.5)	4.52 ± 1.16 (0.06)	0.97 ± 0.04	0.1 ± 0.22 (0.9)	Medium (0.5)	na	0.83	0.59
Mammal	PPGO	3 (0)	5 ± 1 (0.13)	0.28 ± 0.46	0.33 ± 0.58 (0.67)	Low (0)	na	0.59	0.32
Mammal	OBPM	28 (0.5)	5.89 ± 2.13 (0.24)	0.67 ± 0.13	0.47 ± 0.36 (0.53)	Medium (0.5)	na	0.91	0.59
Mammal	PPMO	11 (0)	7.91 ± 2.21 (0.49)	0.91 ± 0.1	0.15 ± 0.34 (0.85)	Medium (0.5)	na	0.64	0.5
Mammal	SPMO	3 (0)	4.67 ± 0.58 (0.08)	0.99 ± 0.01	0.67 ± 0.58 (0.33)	Low (0)	na	0.98	0.49
Mammal	GBPM	17 (0)	6.18 ± 2.48 (0.27)	0.93 ± 0.05	0.1 ± 0.21 (0.9)	Medium (0.5)	na	0.93	0.59
Mammal	HPMO	10 (0)	5.4 ± 2.22 (0.18)	0.98 ± 0.02	0.3 ± 0.48 (0.7)	Medium (0.5)	na	0.75	0.49
Mammal	PLHM	7 (0)	6.43 ± 3.1 (0.3)	0.65 ± 0.45	0.43 ± 0.53 (0.57)	Low (0)	na	0.67	0.4
Mammal	CAMO	3 (0)	4.67 ± 1.15 (0.08)	0.3 ± 0.48	0.67 ± 0.58 (0.33)	Low (0)	na	0.51	0.26
Mammal	PIMO	2 (0)	4 ± 0 (0)	0.1 ± 0.21	0 ± 0 (1)	Low (0)	na	1	0.46
Mammal	WHVO	7 (0)	5.29 ± 0.76 (0.16)	0.69 ± 0.47	0.14 ± 0.38 (0.86)	Low (0)	na	0.49	0.34
Mammal	PRVO	24 (0.5)	5.75 ± 1.39 (0.22)	0.78 ± 0.12	0.32 ± 0.34 (0.68)	Medium (0.5)	na	0.9	0.6
Mammal	WAVO	77 (0.75)	6.06 ± 2.36 (0.26)	0.94 ± 0.02	0.14 ± 0.14 (0.86)	Medium (0.5)	0.75 ± 0.21	0.51	0.6
Mammal	SBVO	31 (0.5)	5.71 ± 2.42 (0.21)	0.76 ± 0.1	0.33 ± 0.27 (0.68)	Medium (0.5)	na	0.86	0.59
Mammal	PMJM	48 (0.5)	10.44 ± 2.4 (0.8)	0.98 ± 0.01	0.04 ± 0.08 (0.96)	High (1)	0.83 ± 0.28	0.96	0.87
Mammal	BMJM	20 (0.5)	6.05 ± 3.53 (0.26)	0.98 ± 0.03	0.1 ± 0.21 (0.9)	Medium (0.5)	na	0	0.32
Mammal	SWFO	223 (1)	6.64 ± 1.68 (0.33)	0.94 ± 0.02	0.13 ± 0.06 (0.87)	High (1)	0.88 ± 0.13	0.9	0.84

Taxonomic Class	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Boyce Index (BI)	Exposure Change; (EC)	CI
Mammal	GRBE	639 (1)	7.07 ± 1.22 (0.38)	0.94 ± 0	0.04 ± 0.03 (0.96)	High (1)	0.64 ± 0.31	0.84	0.82
Mammal	RING	7 (0)	7.14 ± 2.04 (0.39)	0.63 ± 0.44	0.29 ± 0.49 (0.71)	Low (0)	na	0.96	0.53
Mammal	MART	202 (1)	6.4 ± 1.8 (0.3)	0.94 ± 0.01	0.07 ± 0.05 (0.93)	High (1)	0.76 ± 0.19	0.89	0.83
Mammal	FISH	14 (0)	4.93 ± 2.56 (0.12)	0.91 ± 0.09	0.2 ± 0.42 (0.8)	Medium (0.5)	na	0.82	0.52
Mammal	LEWE	9 (0)	6.22 ± 2.33 (0.28)	0.99 ± 0.01	0.11 ± 0.33 (0.89)	Medium (0.5)	na	0.55	0.46
Mammal	BFFE	4 (0)	5.25 ± 2.5 (0.16)	0.38 ± 0.49	0.5 ± 0.58 (0.5)	Low (0)	na	1	0.46
Mammal	WOLV	192 (1)	6.16 ± 2.5 (0.27)	0.92 ± 0.03	0.12 ± 0.08 (0.88)	High (1)	0.06 ± 0.66	0.54	0.63
Mammal	RIOT	202 (1)	6.46 ± 2.5 (0.31)	0.86 ± 0.04	0.24 ± 0.09 (0.76)	Medium (0.5)	0.99 ± 0.03	0.81	0.76
Mammal	CALY	232 (1)	5.84 ± 1.54 (0.23)	0.93 ± 0.03	0.1 ± 0.09 (0.9)	High (1)	0.69 ± 0.33	0.69	0.74
Mammal	MOOS	4930 (1)	6.73 ± 1.44 (0.34)	0.64 ± 0.01	0.18 ± 0.02 (0.82)	High (1)	0.97 ± 0.05	0.95	0.84
Mammal	BISH	1716 (1)	6.76 ± 1.47 (0.34)	0.8 ± 0.02	0.24 ± 0.03 (0.76)	High (1)	0.98 ± 0.04	0.88	0.83
Reptile	WPTU	21 (0.5)	9.43 ± 2.48 (0.68)	0.93 ± 0.06	0.2 ± 0.35 (0.8)	Low (0)	na	0.88	0.64
Reptile	WSSS	19 (0)	7.42 ± 2.67 (0.43)	0.85 ± 0.16	0.25 ± 0.35 (0.75)	Low (0)	na	0.78	0.49
Reptile	GPEL	7 (0)	5.43 ± 1.4 (0.18)	0.69 ± 0.47	0.43 ± 0.53 (0.57)	Low (0)	na	0.77	0.42
Reptile	GSHO	148 (1)	8.11 ± 2.47 (0.51)	0.81 ± 0.05	0.19 ± 0.13 (0.81)	High (1)	na	0.95	0.79
Reptile	NSBL	112 (1)	9.54 ± 3 (0.69)	0.86 ± 0.05	0.19 ± 0.13 (0.81)	Medium (0.5)	0.79 ± 0.17	0.91	0.83
Reptile	PFLI	34 (0.5)	7.26 ± 3.6 (0.41)	0.92 ± 0.04	0.29 ± 0.23 (0.71)	Low (0)	na	0.89	0.6
Reptile	PRLI	3 (0)	7 ± 1.73 (0.38)	0.3 ± 0.48	0.33 ± 0.58 (0.67)	Low (0)	na	0.47	0.31
Reptile	NTLI	13 (0)	7.62 ± 3.25 (0.45)	0.99 ± 0.01	0.05 ± 0.16 (0.95)	Medium (0.5)	na	0.77	0.56
Reptile	NMLS	6 (0)	4.17 ± 0.41 (0.02)	0.97 ± 0.5	0.5 ± 0.55 (0.5)	Low (0)	na	0.81	0.43
Reptile	PRRR	4 (0)	4.5 ± 1 (0.06)	0.4 ± 0.51	0.5 ± 0.58 (0.5)	Low (0)	na	0.92	0.43
Reptile	RUBO	51 (0.75)	6.9 ± 2.09 (0.36)	0.9 ± 0.04	0.25 ± 0.2 (0.75)	Medium (0.5)	0.86 ± 0.15	0.75	0.7
Reptile	EYBR	60 (0.75)	7.63 ± 3.2 (0.45)	0.86 ± 0.06	0.13 ± 0.15 (0.87)	Medium (0.5)	0.79 ± 0.2	0.8	0.73
Reptile	PHNS	22 (0.5)	7.32 ± 3.05 (0.41)	0.83 ± 0.13	0 ± 0 (1)	Medium (0.5)	na	0.85	0.65
Reptile	PAMS	19 (0)	6.26 ± 1.79 (0.28)	0.9 ± 0.1	0.3 ± 0.26 (0.7)	Low (0)	na	0.74	0.45

Taxonomic Class	Species Code	Number Occur. (NOS)	Mean Occur. Quality (OQS)	Mean Test AUC	Mean Test Omission Error (OES)	Expert Review (ERS)	Boyce Index (BI)	Exposure Change; (EC)	CI
Reptile	GBGS	15 (0)	6.93 ± 2.79 (0.37)	0.94 ± 0.05	0.1 ± 0.21 (0.9)	Medium (0.5)	na	0.89	0.58
Reptile	BULL	145 (1)	8.67 ± 2.82 (0.58)	0.82 ± 0.03	0.21 ± 0.1 (0.79)	Medium (0.5)	0.88 ± 0.09	0.92	0.82
Reptile	BHRS	8 (0)	7.75 ± 3.06 (0.47)	0.78 ± 0.41	0.13 ± 0.35 (0.88)	Low (0)	na	0	0.21
Reptile	WAGS	129 (1)	8.19 ± 3.08 (0.52)	0.7 ± 0.08	0.36 ± 0.14 (0.64)	Low (0)	0.77 ± 0.28	0.89	0.72
Reptile	PLGA	18 (0)	6.5 ± 2.92 (0.31)	0.8 ± 0.2	0.35 ± 0.41 (0.65)	Medium (0.5)	na	0.92	0.56
Reptile	RSGS	32 (0.5)	7.78 ± 1.91 (0.47)	0.85 ± 0.07	0.27 ± 0.22 (0.73)	Medium (0.5)	na	0.74	0.59
Reptile	VAGS	2 (0)	9 ± 1.41 (0.63)	0.1 ± 0.21	0 ± 0 (1)	Low (0)	na	1	0.55
Reptile	SGSN	24 (0.5)	7.5 ± 2.99 (0.44)	0.92 ± 0.16	0.13 ± 0.32 (0.87)	Medium (0.5)	na	0.83	0.64
Reptile	PRRS	281 (1)	6.88 ± 2.07 (0.36)	0.78 ± 0.03	0.36 ± 0.1 (0.64)	Medium (0.5)	0.82 ± 0.11	0.93	0.77
Reptile	MFRS	35 (0.5)	9.6 ± 3.28 (0.7)	0.97 ± 0.03	0.03 ± 0.11 (0.97)	Medium (0.5)	na	0.83	0.69

Appendix D: Studies used to create Figure 1 of Chapter 3

The results of studies listed in Table D1 were used to create Figure 1 of Chapter 3. These studies were identified based on a of Web of Science^{TM} search for published literature investigating species characteristics that influence sensitivity to disturbance and/or extinction proneness. The search contained title keywords (extinct* OR sensitiv* OR decline* OR endanger* OR vulnerab*) AND (species OR mammal* OR bird OR avian OR amphibian OR reptile OR herptile*), as well as topic key words keywords (mammal* OR bird OR avian OR amphibian OR reptile OR herptile*) AND (trait* OR "life history" OR charact*). From the resulting list of 166 studies, we identified those that statistically tested the effects of multiple traits for terrestrial vertebrate species using actual data (i.e., we excluded simulation models) and excluding those based on fossil records. We used backward and forward citation links to identify additional studies.

Studies were classified according to the geographic scale of their analysis and the type of response variable used. Global, continental or regional studies were classified as "large", while studies of specific localities or comparatively small areas (e.g., specific mountain ranges, or portions of countries, states or provinces) were classified as "small". Response variables that were based on synthetic assessments of species endangerment or conservation status (e.g., IUCN Red List categories) were classified as "Score", while studies using actual measures of species decline (e.g., local extinction, relative abundance, proportion of area occupied) were classified as "Decline".

When a trait was deemed important by the authors of a given study, the result is classified as "Significant." This generally refers to statistical significance, but can sometimes refer to other measures of importance in more complex analyses (e.g., traits identified in an optimal classification or regression tree, terms retained in an optimal model based on AIC model selection). Similarly, "No Effect" generally refers to lack of statistical significance, but can also refer to a trait not being included in a confidence set based on model selection. Effect direction is the result of an increase in the predictor variable and is measured relative to the response variable (e.g., if the trait is a measure of body size, "increased risk" refers to larger species being in more threatened categories of an endangerment score). If the direction of effect is unclear from the study (e.g., interactions with other variables change the effect) then the direction is listed as "Complex". When a citation included two distinct tests of a given characteristic (e.g., testing the effect of body size on endangerment separately for amphibians and reptiles or testing the effect of body size on local avian extinctions using two different response variables), then there is one row in the table for each test.

Table D1. Studies used to generate Figure 1 of Chapter 3. Each study investigates the effect of species characteristics relative to risk of endangerment or decline for A) Body Size, B) Geographic Range, C) Ecological Specialization, D) Reproductive Output, or E) Rarity, where letters refer to the corresponding panel of Figure 1. . Effect direction refers to the response resulting from an increase in the given characteristic.

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
A	Amano and Yamaura 2007	Large	Decline	Birds	Body Size - Mass	Significant	Complex
A	Benchimol and Peres 2014	Large	Decline	Mammals	Body Size - Mass	No Effect	-
A	Biedermann 2003	Small	Decline	Various	Body Size - Mass	Significant	Increased Risk
A	Bielby et al. 2008	Large	Score	Amphibians	Body Size - Length	No Effect	-
A	Blumstein 2006	Small	Decline	Birds	Body Size - Mass	Significant	Increased Risk
A	Brashares 2003	Small	Decline	Mammals	Body Size - Mass	No Effect	Decreased Risk
A	Cardillo et al. 2005	Large	Score	Mammals	Body Size - Mass	Significant	Increased Risk
A	Castelletta et al 2000	Small	Decline	Birds	Body Size - Mass	No Effect	Increased Risk
A	Cooper et al 2008	Large	Score	Amphibians	Body Size - Length	No Effect	-
A	Crooks 2002	Small	Decline	Mammals	Body Size - Mass	No Effect	-
A	Davidson et al. 2009	Large	Score	Mammals	Body Size - Mass	Significant	Increased Risk
A	de Castro and Fernandez 2004	Small	Decline	Mammals	Body Size - Mass	No Effect	-
A	Di Marco et al 2014	Large	Score	Mammals	Body Size - Neonatal Mass	Significant	Complex
A	Feeley et al. 2007	Small	Decline	Birds	Body Size - Length	Significant	Increased Risk
A	Fisher et al 2003	Large	Score	Mammals	Body Size - Mass	Significant	Increased Risk
A	Fisher et al 2003	Large	Decline	Mammals	Body Size - Mass	Significant	Decreased Risk
A	Foufopoulos and Ives 1999	Small	Decline	Reptiles	Body Size - Mass	No Effect	Increased Risk
A	Fritz et al 2009	Large	Score	Mammals	Body Size - Mass	Significant	Complex
A	Gaston and Blackburn 1995	Large	Score	Birds	Body Size - Mass	Significant	Increased Risk
A	Gonzalez-Suarez and Revilla 2013	Large	Score	Mammals	Body Size - Mass	No Effect	Complex
A	Gonzalez-Suarez and Revilla 2013	Large	Decline	Mammals	Body Size - Mass	Significant	Increased Risk

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
A	Gray et al. 2007	Small	Decline	Birds	Body Size - Mass	Significant	Increased Risk
A	Hager 1998	Small	Decline	Herptiles	Body Size - Mass	No Effect	-
A	Hanna and Cardillo 2014	Large	Decline	Mammals	Body Size - Mass	Significant	Increased Risk
A	Harcourt 1998	Small	Decline	Mammals	Body Size - Mass	No Effect	Increased Risk
A	Hero et al 2005	Large	Score	Amphibians	Body Size - Length	No Effect	-
A	Isaac and Cowlishaw 2004	Small	Decline	Mammals	Body Size - Mass	Significant	Increased Risk
A	Isaac and Cowlishaw 2004	Small	Decline	Mammals	Body Size - Mass	No Effect	-
A	Jennings and Pocock 2009	Small	Decline	Mammals	Body Size - Mass	No Effect	-
A	Johnson et al. 2002	Large	Score	Mammals	Body Size - Mass	Significant	Complex
A	Jones et al 2001	Small	Decline	Birds	Body Size - Wing Length	No Effect	Increased Risk
A	Jones et al 2006	Large	Score	Birds	Body Size - Length	No Effect	-
A	Jones et al. 2003	Large	Score	Mammals	Body Size - Mass	No Effect	-
A	Kattan et al 1994	Small	Decline	Birds	Body Size - Mass	Significant	Increased Risk
A	Kolecek et al 2014	Large	Score	Birds	Body Size - Mass	No Effect	-
A	Laurance 1991	Small	Decline	Mammals	Body Size - Mass	No Effect	Increased Risk
A	Lee and Jetz 2011	Large	Score	Birds	Body Size - Mass	Significant	Increased Risk
A	Lees and Perez 2008	Small	Decline	Birds	Body Size - Mass	Significant	Decreased Risk
A	Lima et al 1996	Small	Decline	Mammals	Body Size - Mass	No Effect	-
A	Lips et al 2003	Small	Decline	Amphibians	Body Size - Length	Significant	Increased Risk
A	Mace and Balmford 2000	Large	Score	Mammals	Family Typical Body Size	No Effect	-
A	Machado and Loyola 2013	Large	Score	Birds	Body Size - Mass	No Effect	-
A	Murray and Hose 2005	Large	Score	Amphibians	Body Size - Length	Significant	Increased Risk
A	Newbold et al. 2013	Small	Decline	Birds	Body Size - Mass	Significant	Complex
A	Newmark 1989	Small	Decline	Birds	Body Size - Mass	No Effect	-
A	Newmark 1991	Small	Decline	Birds	Body Size - Mass	No Effect	-
A	Newmark 1995	Small	Decline	Mammals	Body Size - Mass	No Effect	-
A	Newmark et al. 2014	Small	Decline	Mammals	Body Size - Mass	No Effect	-
A	Norris and Harper 2004	Large	Score	Birds	Body Size - Mass	Significant	Increased Risk

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
A	Nupp and Swihart 2000	Small	Decline	Mammals	Body Size - Mass	No Effect	-
A	Okie and Brown 2009	Large	Decline	Various	Body Size - Mass	Significant	Complex
A	Owens and Bennett 2000	Large	Score	Birds	Family Typical Body Size	Significant	Increased Risk
A	Owens and Bennett 2000	Large	Score	Birds	Family Typical Body Size	Significant	Decreased Risk
A	Patten and Smith-Patten 2011	Small	Decline	Birds	Body Size - Mass	Significant	Complex
A	Pimm et al. 1988	Small	Decline	Birds	Body Size: Large Pops	Significant	Increased Risk
A	Pimm et al. 1988	Small	Decline	Birds	Body Size: Small Pops	Significant	Decreased Risk
A	Pineda and Halffter 2003	Small	Decline	Amphibians	Body Size - Mass	No Effect	-
A	Pineda and Halffter 2003	Small	Decline	Amphibians	Body Size - Mass	Significant	Increased Risk
A	Pocock 2011	Large	Decline	Birds	Body Size - Mass	Significant	Complex
A	Polishchuk 2002	Large	Score	Mammals	Body Size - Mass	Significant	Increased Risk
A	Purvis et al. 2000	Large	Score	Mammals	Body Size - Mass	No Effect	-
A	Purvis et al. 2000	Large	Score	Mammals	Body Size - Mass	Significant	Increased Risk
A	Quesnelle et al. 2014	Small	Decline	Various	Body Size - Mass	No Effect	-
A	Robinson et al. 1992	Small	Decline	Mammals	Body Size - Mass	Significant	Increased Risk
A	Rosenweig and Clark 1994	Small	Decline	Birds	Body Size - Mass	No Effect	-
A	Senior et al. 2013	Small	Decline	Birds	Body Size - Mass	No Effect	Increased Risk
A	Shultz et al 2005	Large	Decline	Birds	Body Size - Mass	No Effect	-
A	Siriwardena et al 1998	Large	Decline	Birds	Body Size - Mass	No Effect	-
A	Smith and Quin 1996	Large	Decline	Mammals	Body Size - Mass	Significant	Increased Risk
A	Sodhi et al 2008	Large	Score	Amphibians	Body Size - Mass	Significant	Increased Risk
A	Sodhi et al 2008	Large	Decline	Amphibians	Body Size - Mass	Significant	Increased Risk
A	Tingley et al 2013	Large	Score	Reptiles	Body Size - Mass	Significant	Increased Risk
A	Tracy and George 1992	Small	Decline	Birds	Body Size - Mass	No Effect	-
A	Vetter et al 2010	Small	Decline	Birds	Body Size - Mass	No Effect	-
A	Wang et al 2010	Small	Decline	Mammals	Body Size - Mass	No Effect	Increased Risk

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
A	Wang et al 2010	Small	Decline	Reptiles	Body Size - Mass	No Effect	Increased Risk
A	Wang et al 2010	Small	Decline	Birds	Body Size - Mass	No Effect	Increased Risk
A	Watling and Donnelly 2007	Small	Decline	Reptiles	Body Size - Mass	No Effect	-
A	Watling and Donnelly 2007	Small	Decline	Amphibians	Body Size - Mass	No Effect	-
B	Amano and Yamaura 2007	Large	Decline	Birds	Geographic Range - Regional	No Effect	-
B	Anjos et al 2010	Small	Decline	Birds	Geographic Range - Global	Significant	Decreased Risk
B	Bielby et al. 2008	Large	Score	Amphibians	Geographic Range - Global	Significant	Complex
B	Cardillo et al. 2005	Large	Score	Mammals	Geographic Range - Global	Significant	Decreased Risk
B	Cooper et al 2008	Large	Score	Amphibians	Geographic Range - Global	Significant	Complex
B	Davidson et al. 2009	Large	Score	Mammals	Geographic Range - Global	Significant	Decreased Risk
B	Feeley et al. 2007	Small	Decline	Birds	Geographic Range - Latitude Range	Significant	Increased Risk
B	Fisher et al 2003	Large	Score	Mammals	Geographic Range - Global	No Effect	-
B	Fisher et al 2003	Large	Decline	Mammals	Geographic Range - Global	Significant	Increased Risk
B	Fritz et al 2009	Large	Score	Mammals	Geographic Range - Global	Significant	Decreased Risk
B	Gonzalez-Suarez and Revilla 2013	Large	Score	Mammals	Geographic Range - Global	Significant	Decreased Risk
B	Gray et al. 2007	Small	Decline	Birds	Geographic Range - Global	Significant	Decreased Risk
B	Harcourt 1998	Small	Decline	Mammals	Geographic Range - Latitude Range	Significant	Decreased Risk
B	Harcourt 1998	Small	Decline	Mammals	Geographic Range - Local	No Effect	-
B	Hero et al 2005	Large	Score	Amphibians	Geographic Range - Latitude Range	No Effect	Decreased Risk
B	Hero et al 2005	Large	Score	Amphibians	Geographic Range - Global	Significant	Decreased Risk
B	Jones et al 2006	Large	Score	Birds	Geographic Range - Latitude Range	Significant	Complex

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
B	Jones et al 2006	Large	Score	Birds	Geographic Range - Number of Islands Occupied	No Effect	-
B	Jones et al. 2003	Large	Score	Mammals	Geographic Range - Global	Significant	Decreased Risk
B	Kolecek et al 2014	Large	Score	Birds	Geographic Range - Local	Significant	Increased Risk
B	Lips et al 2003	Small	Decline	Amphibians	Geographic Range - Global	No Effect	-
B	Mace and Kershaw 1997	Small	Score	Birds	Geographic Range - Local	No Effect	Decreased Risk
B	Manne et al. 1999	Large	Score	Various	Geographic Range - Global	Significant	Decreased Risk
B	Newmark et al. 2014	Small	Decline	Mammals	Geographic Range - Global	No Effect	-
B	Ogrady et al 2004	Large	Decline	Various	Geographic Range - Global	No Effect	-
B	Patten and Smith-Patten 2011	Small	Decline	Birds	Geographic Range - Number of Biomes	No Effect	-
B	Purvis et al. 2000	Large	Score	Mammals	Geographic Range - Global	Significant	Decreased Risk
B	Purvis et al. 2000	Large	Score	Mammals	Geographic Range - Global	Significant	Decreased Risk
B	Senior et al. 2013	Small	Decline	Birds	Geographic Range - Global	Significant	Decreased Risk
B	Wang et al 2010	Small	Decline	Birds	Geographic Range - Global	No Effect	Decreased Risk
B	Wang et al 2010	Small	Decline	Reptiles	Geographic Range - Global	No Effect	Decreased Risk
B	Wang et al 2010	Small	Decline	Mammals	Geographic Range - Global	No Effect	Decreased Risk
B	Watling and Donnelly 2007	Small	Decline	Reptiles	Geographic Range - Latitude Range	No Effect	-
B	Watling and Donnelly 2007	Small	Decline	Amphibians	Geographic Range - Latitude Range	No Effect	-
B	Watling and Donnelly 2007	Small	Decline	Amphibians	Geographic Range - Local	No Effect	-
B	Watling and Donnelly 2007	Small	Decline	Reptiles	Geographic Range - Local	No Effect	-
C	Amano and Yamaura 2007	Large	Decline	Birds	Habitat - Specialization	No Effect	-
C	Amano and Yamaura 2007	Large	Decline	Birds	Habitat - Arboreality	No Effect	-

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
C	Anciaes and Marini 2000	Small	Decline	Birds	Habitat - Arboreality	Significant	Decreased Risk
C	Anciaes and Marini 2000	Small	Decline	Birds	Diet - Foraging Guild	Significant	Complex
C	Anciaes and Marini 2000	Small	Decline	Birds	Diet - Insectivory	Significant	Increased Risk
C	Anciaes and Marini 2000	Small	Decline	Birds	Habitat - Forest Dependence	No Effect	-
C	Arriaga-Weiss et al. 2008	Small	Decline	Birds	Diet - Foraging Guild	Significant	Complex
C	Benassi et al. 2007	Small	Decline	Birds	Habitat - Specialization	Significant	Increased Risk
C	Benchimol and Peres 2013	Large	Decline	Mammals	Diet - Class	Significant	Complex
C	Benchimol and Peres 2013	Large	Decline	Mammals	Diet - Frugivory	No Effect	-
C	Benchimol and Peres 2013	Large	Decline	Mammals	Habitat - Forest Dependence	No Effect	-
C	Bielby et al. 2008	Large	Score	Amphibians	Habitat - Altitude Range	Significant	Increased Risk
C	Blake 1991	Small	Decline	Birds	Habitat - Forest Interior Specialization	Significant	Increased Risk
C	Brashares 2003	Small	Decline	Mammals	Habitat - Specialization	No Effect	Increased Risk
C	Canaday 1996	Small	Decline	Birds	Diet - Insectivory	Significant	Complex
C	Canaday and Rivadeneyra 2001	Small	Decline	Birds	Diet - Insectivory	Significant	Increased Risk
C	Castelletta et al 2000	Small	Decline	Birds	Habitat - Forest Dependence	Significant	Increased Risk
C	Castelletta et al 2000	Small	Decline	Birds	Diet - Insectivory	Significant	Increased Risk
C	Cooper et al 2008	Large	Score	Amphibians	Habitat - Specialization	No Effect	-
C	de Castro and Fernandez 2004	Small	Decline	Mammals	Habitat - Arboreality	No Effect	-
C	de Castro and Fernandez 2004	Small	Decline	Mammals	Habitat - Use of Matrix	Significant	Decreased Risk
C	Di Marco et al 2014	Large	Score	Mammals	Diet - Specialization Index	No Effect	-
C	Feeley et al. 2007	Small	Decline	Birds	Diet - Foraging Guild	No Effect	-
C	Feeley et al. 2007	Small	Decline	Birds	Habitat - Specialization	Significant	Increased Risk
C	Fisher et al 2003	Large	Score	Mammals	Diet - Class	Significant	Complex

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
C	Fisher et al 2003	Large	Score	Mammals	Habitat - Specialization	Significant	Decreased Risk
C	Fisher et al 2003	Large	Decline	Mammals	Habitat - Specialization	Significant	Increased Risk
C	Fisher et al 2003	Large	Decline	Mammals	Diet - Class	Significant	Complex
C	Foufopoulos and Ives 1999	Small	Decline	Reptiles	Habitat - Specialization	Significant	Increased Risk
C	Gray et al. 2007	Small	Decline	Birds	Diet - Foraging Guild	Significant	Complex
C	Gray et al. 2007	Small	Decline	Birds	Diet - Frugivory	Significant	Increased Risk
C	Gray et al. 2007	Small	Decline	Birds	Diet - Insectivory	Significant	Increased Risk
C	Harcourt 1998	Small	Decline	Mammals	Habitat - Altitude Range	No Effect	-
C	Harcourt 1998	Small	Decline	Mammals	Habitat - Arboreality	No Effect	-
C	Harcourt 1998	Small	Decline	Mammals	Diet - Class	No Effect	-
C	Hero et al 2005	Large	Score	Amphibians	Habitat - Arboreality	No Effect	Decreased Risk
C	Isaac and Cowlishaw 2004	Small	Decline	Mammals	Habitat - Arboreality	No Effect	-
C	Isaac and Cowlishaw 2004	Small	Decline	Mammals	Diet - Frugivory	Significant	Decreased Risk
C	Isaac and Cowlishaw 2004	Small	Decline	Mammals	Diet - Frugivory	No Effect	-
C	Isaac and Cowlishaw 2004	Small	Decline	Mammals	Habitat - Arboreality	Significant	Increased Risk
C	Johnson et al. 2002	Large	Score	Mammals	Diet - Class	No Effect	Complex
C	Jones et al 2001	Small	Decline	Birds	Habitat - Arboreality	No Effect	-
C	Jones et al 2006	Large	Score	Birds	Habitat - Altitude Range	Significant	-
C	Jones et al 2006	Large	Score	Birds	Habitat - Arboreality	Significant	Increased Risk
C	Jones et al 2006	Large	Score	Birds	Diet - Class	No Effect	-
C	Karr 1982b	Small	Decline	Birds	Habitat - Altitude Range	Significant	Increased Risk
C	Karr 1982b	Small	Decline	Birds	Diet - Class	No Effect	-
C	Karr 1982b	Small	Decline	Birds	Habitat - Arboreality	Significant	Decreased Risk
C	Kattan et al 1994	Small	Decline	Birds	Diet - Foraging Guild	Significant	Complex
C	Kolecek et al 2014	Large	Score	Birds	Habitat - Specialization	Significant	Complex

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
C	Laurance 1991	Small	Decline	Mammals	Diet - Specialization Index	Significant	Increased Risk
C	Lee and Jetz 2011	Large	Score	Birds	Habitat - Specialization	Significant	Increased Risk
C	Lee and Jetz 2011	Large	Score	Birds	Habitat - Altitude Range	No Effect	-
C	Lee and Jetz 2011	Large	Score	Birds	Diet - Class	Significant	Complex
C	Lee and Jetz 2011	Large	Score	Birds	Habitat - Forage Height Breadth	No Effect	-
C	Lee and Jetz 2011	Large	Score	Birds	Diet - Breadth	No Effect	-
C	Lees and Perez 2006	Small	Decline	Birds	Habitat - Forest Dependence	Significant	Increased Risk
C	Lees and Perez 2008	Small	Decline	Birds	Diet - Foraging Guild	Significant	Complex
C	Lees and Perez 2008	Small	Decline	Birds	Habitat - Specialization	Significant	Increased Risk
C	Lees and Perez 2008	Small	Decline	Birds	Habitat - Zoogeographic Regions	No Effect	Decreased Risk
C	Lees and Perez 2008	Small	Decline	Birds	Habitat - Forest Dependence	Significant	Decreased Risk
C	Lips et al 2003	Small	Decline	Amphibians	Habitat - Altitude Range	Significant	Decreased Risk
C	Mace and Kershaw 1997	Small	Score	Birds	Habitat - Specialization	No Effect	-
C	Machado and Loyola 2013	Large	Score	Birds	Habitat - Specialization	No Effect	-
C	Machado and Loyola 2013	Large	Score	Birds	Habitat - Altitude Range	No Effect	-
C	Newbold et al. 2013	Small	Decline	Birds	Diet - Class	Significant	Complex
C	Newbold et al. 2013	Small	Decline	Birds	Habitat - Forest Dependence	Significant	Complex
C	Newmark 1989	Small	Decline	Birds	Diet - Foraging Guild	No Effect	-
C	Newmark 1991	Small	Decline	Birds	Habitat - Forest Interior Specialization	Significant	Increased Risk
C	Newmark 1991	Small	Decline	Birds	Diet - Class	No Effect	-
C	Newmark 1995	Small	Decline	Mammals	Diet - Specialization Index	No Effect	-
C	Newmark 2006	Small	Decline	Birds	Diet - Foraging Guild	Significant	Complex
C	Newmark et al. 2014	Small	Decline	Mammals	Habitat - Use of Matrix	Significant	Decreased Risk

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
C	Norris and Harper 2004	Large	Score	Birds	Habitat - Specialization	Significant	Increased Risk
C	Ogrady et al 2004	Large	Decline	Various	Habitat - Specialization	No Effect	-
C	Owens and Bennett 2000	Large	Score	Birds	Habitat - Specialization	No Effect	-
C	Owens and Bennett 2000	Large	Score	Birds	Habitat - Specialization	Significant	Increased Risk
C	Patten and Smith-Patten 2011	Small	Decline	Birds	Habitat - Altitude Range	No Effect	-
C	Patten and Smith-Patten 2011	Small	Decline	Birds	Habitat - Forest Dependence	Significant	Increased Risk
C	Patten and Smith-Patten 2011	Small	Decline	Birds	Habitat - Specialization	No Effect	-
C	Patten and Smith-Patten 2011	Small	Decline	Birds	Diet - Class	Significant	Complex
C	Pineda and Halffter 2003	Small	Decline	Amphibians	Habitat - Arboreality	No Effect	Complex
C	Pineda and Halffter 2003	Small	Decline	Amphibians	Habitat - Arboreality	Significant	Decreased Risk
C	Pocock 2011	Large	Decline	Birds	Habitat - Specialization	Significant	Increased Risk
C	Prugh et al. 2008	Small	Decline	Various	Habitat - Arboreality	Significant	Increased Risk
C	Prugh et al. 2008	Small	Decline	Various	Habitat - Arboreality	No Effect	-
C	Prugh et al. 2008	Small	Decline	Various	Diet - Class	No Effect	-
C	Prugh et al. 2008	Small	Decline	Various	Habitat - Specialization	No Effect	-
C	Prugh et al. 2008	Small	Decline	Various	Habitat - Specialization	No Effect	-
C	Prugh et al. 2008	Small	Decline	Various	Diet - Class	Significant	Complex
C	Rottenborn 1998	Small	Decline	Birds	Diet - Class	Significant	Complex
C	Sekercioglu et al. 2001	Small	Decline	Birds	Habitat - Forest Dependence	Significant	Increased Risk
C	Sekercioglu et al. 2001	Small	Decline	Birds	Diet - Insectivory	Significant	Increased Risk
C	Senior et al. 2013	Small	Decline	Birds	Diet - Class	Significant	Complex
C	Senior et al. 2013	Small	Decline	Birds	Diet - Insectivory	Significant	Increased Risk
C	Senior et al. 2013	Small	Decline	Birds	Diet - Frugivory	Significant	Increased Risk
C	Shultz et al 2005	Large	Decline	Birds	Habitat - Niche Position	Significant	Decreased Risk
C	Shultz et al 2005	Large	Decline	Birds	Habitat - Specialization	No Effect	-

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
C	Siriwardena et al 1998	Large	Decline	Birds	Diet - Class	No Effect	-
C	Siriwardena et al 1998	Large	Decline	Birds	Habitat - Specialization	Significant	Increased Risk
C	Smith and Quin 1996	Large	Decline	Mammals	Habitat - Shelter Use	Significant	Decreased Risk
C	Smith and Quin 1996	Large	Decline	Mammals	Diet - Class	No Effect	-
C	Sodhi et al 2008	Large	Score	Amphibians	Habitat - Arboreality	No Effect	-
C	Sodhi et al 2008	Large	Decline	Amphibians	Habitat - Arboreality	Significant	Increased Risk
C	Stouffer et al. 2006	Small	Decline	Birds	Diet - Foraging Guild	Significant	Complex
C	Tingley et al 2013	Large	Score	Reptiles	Habitat - Specialization	Significant	Increased Risk
C	Tingley et al 2013	Large	Score	Reptiles	Habitat - Arboreality	No Effect	-
C	Tingley et al 2013	Large	Score	Reptiles	Habitat - Altitude Range	No Effect	-
C	Tingley et al 2013	Large	Score	Reptiles	Diet - Insectivory	No Effect	-
C	Vetter et al 2010	Small	Decline	Birds	Diet - Foraging Guild	Significant	Complex
C	Vetter et al 2010	Small	Decline	Birds	Habitat - Forest Dependence	Significant	Increased Risk
C	Wang et al 2010	Small	Decline	Birds	Habitat - Specialization	Significant	Increased Risk
C	Wang et al 2010	Small	Decline	Mammals	Habitat - Specialization	Significant	Increased Risk
C	Wang et al 2010	Small	Decline	Reptiles	Habitat - Specialization	No Effect	Increased Risk
C	Watling and Donnelly 2007	Small	Decline	Reptiles	Diet - Specialization Index	Significant	Increased Risk
C	Watling and Donnelly 2007	Small	Decline	Reptiles	Habitat - Use of Matrix	No Effect	-
C	Watling and Donnelly 2007	Small	Decline	Amphibians	Habitat - Use of Matrix	Significant	Decreased Risk
D	Amano and Yamaura 2007	Large	Decline	Birds	Fecundity - Annual	Significant	Decreased Risk
D	Benchimol and Peres 2013	Large	Decline	Mammals	Fecund - Rmax	No Effect	-
D	Bielby et al. 2008	Large	Score	Amphibians	Fecund - Litter Size	Significant	Decreased Risk
D	Blumstein 2006	Small	Decline	Birds	Fecund - Age of First Reproduction	No Effect	Increased Risk

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
D	Blumstein 2006	Small	Decline	Birds	Fecund - Weaning Age	No Effect	Increased Risk
D	Blumstein 2006	Small	Decline	Birds	Fecund - Litter Size	No Effect	Decreased Risk
D	Bodmer et al. 1997	Small	Decline	Mammals	Fecund - Rmax	Significant	Decreased Risk
D	Bodmer et al. 1997	Small	Decline	Mammals	Fecund - Generation Length	Significant	Increased Risk
D	Brashares 2003	Small	Decline	Mammals	Fecundity - Lifetime	No Effect	-
D	Cardillo et al. 2005	Large	Score	Mammals	Fecund - Weaning Age	Significant	Increased Risk
D	Cardillo et al. 2005	Large	Score	Mammals	Fecund - Gestation Length	Significant	Decreased Risk
D	Cooper et al 2008	Large	Score	Amphibians	Fecund - Litter Size	No Effect	-
D	Davidson et al. 2009	Large	Score	Mammals	Fecund - Reproductive Rate	Significant	Decreased Risk
D	de Castro and Fernandez 2004	Small	Decline	Mammals	Fecundity - Annual	No Effect	-
D	Di Marco et al 2014	Large	Score	Mammals	Fecund - Litter Size	No Effect	-
D	Di Marco et al 2014	Large	Score	Mammals	Fecund - Weaning Age	Significant	Increased Risk
D	Fisher et al 2003	Large	Score	Mammals	Annual Reproduction	No Effect	-
D	Fisher et al 2003	Large	Decline	Mammals	Annual Reproduction	No Effect	-
D	Fritz et al 2009	Large	Score	Mammals	Fecund - Weaning Age	Significant	Increased Risk
D	Fritz et al 2009	Large	Score	Mammals	Fecund - Gestation Length	Significant	Increased Risk
D	Gonzalez-Suarez and Revilla 2013	Large	Score	Mammals	Fecund - Litter Size	No Effect	-
D	Gonzalez-Suarez and Revilla 2013	Large	Score	Mammals	Fecund - Weaning Age	No Effect	-
D	Gonzalez-Suarez and Revilla 2013	Large	Score	Mammals	Fecund - Age of First Reproduction	Significant	Increased Risk
D	Gonzalez-Suarez and Revilla 2013	Large	Decline	Mammals	Fecund - Age of First Reproduction	Significant	Increased Risk
D	Gonzalez-Suarez and Revilla 2013	Large	Decline	Mammals	Fecund - Weaning Age	Significant	Increased Risk

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
D	Gonzalez-Suarez and Revilla 2013	Large	Decline	Mammals	Fecund - Litter Size	No Effect	-
D	Hero et al 2005	Large	Score	Amphibians	Fecund - Litter Size	Significant	Decreased Risk
D	Jennings and Pocock 2009	Small	Decline	Mammals	Fecund - Litters per Year	No Effect	-
D	Jennings and Pocock 2009	Small	Decline	Mammals	Fecund - Litter Size	Significant	Increased Risk
D	Jones et al 2006	Large	Score	Birds	Fecund - Litter Size	No Effect	-
D	Jones et al. 2003	Large	Score	Mammals	Fecund - Litters per Year	No Effect	-
D	Jones et al. 2003	Large	Score	Mammals	Fecund - Litter Size	No Effect	-
D	Jones et al. 2003	Large	Score	Mammals	Fecund - Gestation Length	No Effect	-
D	Kolecek et al 2014	Large	Score	Birds	Fecund - Litter Size	No Effect	-
D	Kolecek et al 2014	Large	Score	Birds	Fecund - Litters per Year	No Effect	-
D	Kolecek et al 2014	Large	Score	Birds	Fecund - Incubation Period	No Effect	-
D	Laurance 1991	Small	Decline	Mammals	Fecundity - Annual	No Effect	Decreased Risk
D	Lee and Jetz 2011	Large	Score	Birds	Fecund - Litter Size	No Effect	-
D	Machado and Loyola 2013	Large	Score	Birds	Fecund - Litter Size	No Effect	-
D	Murray and Hose 2005	Large	Score	Amphibians	Fecund - Litter Size	No Effect	Increased Risk
D	Murray and Hose 2005	Large	Score	Amphibians	Fecund - Testes Mass	No Effect	Decreased Risk
D	Murray and Hose 2005	Large	Score	Amphibians	Fecund - Ova Size	No Effect	Decreased Risk
D	Newbold et al. 2013	Small	Decline	Birds	Fecund - Generation Length	Significant	Complex
D	Newmark 1995	Small	Decline	Mammals	Fecund - Age of First Reproduction	Significant	Decreased Risk
D	Newmark et al. 2014	Small	Decline	Mammals	Fecundity - Annual	No Effect	-
D	Ogrady et al 2004	Large	Decline	Various	Fecund - Generation Length	No Effect	-
D	Owens and Bennett 2000	Large	Score	Birds	Fecund - Residual Generation Time	No Effect	-

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
D	Owens and Bennett 2000	Large	Score	Birds	Fecund - Residual Generation Time	Significant	Increased Risk
D	Pocock 2011	Large	Decline	Birds	Fecund - Fledging Period	No Effect	-
D	Pocock 2011	Large	Decline	Birds	Fecund - Litters per Year	No Effect	-
D	Pocock 2011	Large	Decline	Birds	Fecund - Incubation Period	Significant	Decreased Risk
D	Pocock 2011	Large	Decline	Birds	Fecund - Litter Size	No Effect	-
D	Polishchuk 2002	Large	Score	Mammals	Fecund - Litter Size	Significant	Decreased Risk
D	Polishchuk 2002	Large	Score	Mammals	Fecundity - Annual	Significant	Decreased Risk
D	Polishchuk 2002	Large	Score	Mammals	Fecundity - Lifetime	Significant	Decreased Risk
D	Prugh et al. 2008	Small	Decline	Various	Fecundity - Annual	No Effect	-
D	Prugh et al. 2008	Small	Decline	Various	Fecundity - Annual	No Effect	-
D	Purvis et al. 2000	Large	Score	Mammals	Fecund - Litter Size	No Effect	-
D	Purvis et al. 2000	Large	Score	Mammals	Fecund - Litter Size	No Effect	-
D	Purvis et al. 2000	Large	Score	Mammals	Fecund - Age of First Reproduction	No Effect	-
D	Purvis et al. 2000	Large	Score	Mammals	Fecund - Gestation Length	Significant	Increased Risk
D	Purvis et al. 2000	Large	Score	Mammals	Fecund - Gestation Length	No Effect	-
D	Purvis et al. 2000	Large	Score	Mammals	Fecund - Interbirth Interval	No Effect	-
D	Purvis et al. 2000	Large	Score	Mammals	Fecund - Interbirth Interval	No Effect	-
D	Purvis et al. 2000	Large	Score	Mammals	Fecund - Age of First Reproduction	Significant	Decreased Risk
D	Quesnelle et al. 2014	Small	Decline	Various	Fecund - Reproductive Rate	Significant	Decreased Risk
D	Shultz et al 2005	Large	Decline	Birds	Fecundity - Annual	No Effect	-
D	Siriwardena et al 1998	Large	Decline	Birds	Fecund - Litter Size	No Effect	-
D	Siriwardena et al 1998	Large	Decline	Birds	Fecund - Weaning Age	No Effect	-

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
D	Siriwardena et al 1998	Large	Decline	Birds	Fecund - Litters per Year	No Effect	-
D	Smith and Quin 1996	Large	Decline	Mammals	Fecund - Reproductive Rate	Significant	Decreased Risk
D	Tingley et al 2013	Large	Score	Reptiles	Fecund - Litter Size	No Effect	-
D	Tingley et al 2013	Large	Score	Reptiles	Egg Laying verus Live Birth	No Effect	-
D	Watling and Donnelly 2007	Small	Decline	Reptiles	Fecundity - Annual	No Effect	-
D	Watling and Donnelly 2007	Small	Decline	Amphibians	Fecundity - Annual	No Effect	-
E	Berger 1990	Large	Decline	Mammals	Population Size	Significant	Decreased Risk
E	Bolger et al. 1991	Small	Decline	Birds	Population Density	Significant	Decreased Risk
E	Brashares 2003	Small	Decline	Mammals	Population Size	No Effect	-
E	Cardillo et al. 2005	Large	Score	Mammals	Population Density	Significant	Decreased Risk
E	Davidson et al. 2009	Large	Score	Mammals	Population Density	Significant	Decreased Risk
E	de Castro and Fernandez 2004	Small	Decline	Mammals	Population Density	No Effect	-
E	Feeley et al. 2007	Small	Decline	Birds	Population - Natural Abundance	Significant	Decreased Risk
E	Foufopoulos and Ives 1999	Small	Decline	Reptiles	Population Density	Significant	Decreased Risk
E	Fritz et al 2009	Large	Score	Mammals	Population Density	Significant	Decreased Risk
E	Gonzalez-Suarez and Revilla 2013	Large	Score	Mammals	Population Density	Significant	Decreased Risk
E	Gonzalez-Suarez and Revilla 2013	Large	Decline	Mammals	Population Density	No Effect	-
E	Gray et al. 2007	Small	Decline	Birds	Population Size	Significant	Increased Risk
E	Hager 1998	Small	Decline	Herptiles	Population - Natural Abundance	No Effect	-
E	Harcourt 1998	Small	Decline	Mammals	Geographic Density	No Effect	Decreased Risk
E	Harcourt 1998	Small	Decline	Mammals	Population Density	No Effect	-
E	Laurance 1991	Small	Decline	Mammals	Population - Natural Abundance	No Effect	Decreased Risk

Fig. 1 Panel	Citation	Scale of Study	Response Type	Species Group	Trait	Test Result	Effect Direction
E	Lees and Perez 2008	Small	Decline	Birds	Population - Natural Abundance	Significant	Increased Risk
E	Lima et al 1996	Small	Decline	Mammals	Population Density	Significant	Decreased Risk
E	Mace and Kershaw 1997	Small	Score	Birds	Population Size	Significant	Decreased Risk
E	Newmark 1989	Small	Decline	Birds	Population - Natural Abundance	Significant	Decreased Risk
E	Newmark 1991	Small	Decline	Birds	Population Size	Significant	Decreased Risk
E	Newmark 1995	Small	Decline	Mammals	Population Size	Significant	Decreased Risk
E	Ogrady et al 2004	Large	Decline	Various	Population Size	Significant	Decreased Risk
E	Patten and Smith-Patten 2011	Small	Decline	Birds	Population - Natural Abundance	Significant	Decreased Risk
E	Pimm et al. 1988	Small	Decline	Birds	Population Size	Significant	Decreased Risk
E	Purvis et al. 2000	Large	Score	Mammals	Population Density	Significant	Decreased Risk
E	Purvis et al. 2000	Large	Score	Mammals	Population Density	Significant	Decreased Risk
E	Senior et al. 2013	Small	Decline	Birds	Population Size	Significant	Increased Risk
E	Tracy and George 1992	Small	Decline	Birds	Population Size	Significant	Decreased Risk
E	Watling and Donnelly 2007	Small	Decline	Amphibians	Population - Natural Abundance	Significant	Decreased Risk
E	Watling and Donnelly 2007	Small	Decline	Reptiles	Population - Natural Abundance	No Effect	-

Appendix E: Studies used in analysis investigating predictors of species sensitivity

Table E1. Studies used in analyses investigating predictors of species sensitivity (Chapter 3). Patch and landscape characteristics were drawn from the citations provided. Estimates of time since fragmentation that are given as repeated numbers (e.g., 111 years) are coarse estimates derived from textual explanations (e.g., approximate time of human cultivation of an agricultural area). The absolute value of latitude was used for analyses.

Study Citation	Patch Habitat	Matrix Habitat	Landscape Size (km^2)	Number of Patches	Time Since Frag. (years)	Latitude (deg.)
(Arnold et al. 2003)	Forest	Agriculture	400	24	60	-31
(Battisti et al. 2009)	Forest	Urban	3200	20	222	42
(Bellamy et al. 1998)	Forest	Agriculture	500	28	199	52
(Blake 1991)	Forest	Agriculture	15000	12	190	40
(Bolger et al. 1997)	Shrub	Urban	520	25	36	33
(Brotons et al. 2004)	Forest	Semi-natural	1200	28	18	15
(Cabrera-Guzman and Hugo Reynoso 2012)	Forest	Agriculture	48	8	35	19
(Caceres et al. 2010)	Forest	Agriculture	540	5	55	-20
(Caplat and Fonderflick 2009)	Grass	Agriculture	1600	56	50	21
(Carvajal-Cogollo and Nicolas Urbina-Cardona 2008)	Forest	Agriculture	1147	6	55	8
(Charles and Ang 2010)	Forest	Urban	875	7	55	5
(Crooks 2002)	Shrub	Urban	373	39	43	33
(Dinesen et al. 2001)	Forest	Agriculture	35556	19	55	-8
(Dunning et al. 1995)	Forest	Agriculture	450	19	40	34
(Fernandez-Juricic 2004)	Forest	Urban	360	22	222	40
(Fitzsimons et al. 2011)	Forest	Urban	600	39	165	-38
(Flaspohler et al. 2010)	Forest	Semi-natural	132	19	155	20
(Forys and Humphrey 1999)	Shrub	Urban	700	59	55	25
(Franken and Hik 2004)	Grass	Semi-natural	3	25	555	61
(Ganzhorn 1999)	Forest	Agriculture	2488	13	30	6
(Ganzhorn 2003)	Forest	Agriculture	640000	10	30	-32
(Gehring and Swihart 2003)	Forest	Agriculture	812	45	77	40
(Gottfried 1979)	Forest	Agriculture	31	10	111	42
(Grayson and Livingston 1993)	Forest	Semi-natural	480858	19	5555	39
(Gressler 2008)	Grass	Agriculture	30	6	10	-30
(Hager 1998)	Forest	Semi-natural	42150	63	1111	43
(Hanser and Huntly 2006)	Shrub	Agriculture	6000	11	2100	43
(Hanser and Huntly 2006)	Shrub	Agriculture	1000	11	100	44

Study Citation	Patch Habitat	Matrix Habitat	Landscape Size (km^2)	Number of Patches	Time Since Frag. (years)	Latitude (deg.)
(Hecnar and McLoskey 1996)	Forest	Agriculture	22297	180	150	42
(Helzer and Jelinski 1999)	Grass	Semi-natural	175	38	11	41
(Herkert 1994)	Grass	Agriculture	41250	24	99	40
(Hinsley et al. 1996)	Forest	Agriculture	2450	164	200	52
(Hokit et al. 1999)	Shrub	Semi-natural	75	95	111	28
(Kitchener et al. 1980a)	Grass	Agriculture	140000	23	65	-32
(Kitchener et al. 1980b)	Grass	Agriculture	140000	23	65	-32
(Lawes et al. 2000)	Forest	Agriculture	1500	199	100	-29
(Lens et al. 2002)	Forest	Agriculture	430	12	33	-2
(Lindenmayer and Lacy 2002)	Forest	Semi-natural	450	39	22	-36
(Litteral and Wu 2012)	Shrub	Urban	2025	15	70	33
(Lomolino and Davis 1997)	Forest	Semi-natural	632857	24	5555	33
(Lomolino and Perault 2001)	Forest	Semi-natural	600	20	60	47
(Martınez-Morales 2005)	Forest	Agriculture	2000	13	222	21
(Matthiae and Stearns 1981)	Forest	Urban	525	22	40	42
(McAlpine et al. 2006)	Forest	Urban	2500	352	96	-26
(McCollin 1993)	Forest	Agriculture	2500	16	888	54
(Mesquita and Passamani 2012)	Forest	Agriculture	4	5	55	-21
(Newmark 1986)	Forest	Agriculture	3568235	24	150	45
(Newmark 1991)	Forest	Agriculture	77	10	98	-5
(Nupp and Swihart 2000)	Forest	Agriculture	259	37	150	40
(Onderdonk and Chapman 2000)	Forest	Agriculture	766	20	200	0
(Pardini et al. 2005)	Forest	Agriculture	430	12	65	-24
(Patterson and Atmar 1986)	Forest	Semi-natural	18000000	28	12000	39
(Pineda and Halffter 2004)	Forest	Agriculture	270	10	111	20
(Ramanamanjato and Ganzhorn 2001)	Forest	Semi-natural	80	10	44	-25
(Rao et al. 2008)	Grass	Urban	625	7	160	38
(Reunanen et al. 2002)	Forest	Semi-natural	5525	207	100	66
(Rosenblatt et al. 1999)	Forest	Agriculture	12000	10	190	40
(Santos et al. 2002)	Forest	Agriculture	7850	214	60	40
(Sarre et al. 1995)	Forest	Agriculture	1680	32	95	-31
(Shake et al. 2012)	Shrub	Agriculture	15000	43	10	36
(Silva et al. 2003)	Forest	Agriculture	5000	11	222	46
(Abensperg-Traun et al. 1996)	Shrub	Agriculture	1680	24	50	-32

Study Citation	Patch Habitat	Matrix Habitat	Landscape Size (km^2)	Number of Patches	Time Since Frag. (years)	Latitude (deg.)
(Soulé et al. 1988)	Shrub	Urban	373	37	35	37
(Stone et al. 2009)	Forest	Agriculture	11250	4	22	-2
(Stouffer et al. 2011)	Forest	Agriculture	99	11	30	-3
(Tigas et al. 2003)	Shrub	Urban	216	12	40	34
(Umapathy and Kumar 2000)	Forest	Agriculture	987	25	111	10
(Vallan 2000)	Forest	Agriculture	200	7	111	-18
(Van Buskirk 2005)	Forest	Agriculture	900	88	111	48
(Verbeylen et al. 2003)	Forest	Agriculture	102	54	555	51
(Villard et al. 1999)	Forest	Agriculture	300	45	70	45
(Virgos et al. 2011)	Forest	Agriculture	150000	280	40	41
(Wang et al. 2010)	Forest	Semi-natural	580	46	50	30
(Watson 2003)	Forest	Semi-natural	120000	17	5000	16
(Watson et al. 2004)	Forest	Semi-natural	150	31	50	-25
(Weddell 1991)	Grass	Agriculture	30	67	55	47
(Zimmerman and Bierregaard 1986)	Forest	Agriculture	99	7	30	-3

Appendix F: Results of regressions used to estimate missing reproductive data

Reproductive variables considered in this analysis included age at first reproduction (AFR), maximum lifespan (ML), litter/clutch size (LS), and litters/clutches per year (LPY). Complete sets of reproductive data were not available for many species. In particular AFR was missing for 23% of species, LS was missing for 16% of species, LPY was missing for 45% of species, and ML was missing for 24% of species. We conducted simple linear regressions using the lm function in R version 3.1.1 (R Development Core Team, http://www.r-project.org) to estimate missing values based on body mass (BM; grams) within taxonomic order and family. Specifically, we used the following formulas to develop these allometric models:

*Log(TRAIT) ~ log(BM) + Family + log(BM)*Family*

*log(TRAIT) ~ log(BM) + Order + log(BM)*Order*

Predictions based on family were generally better than those based on order (Table F1), so we used the family-based models to make predictions. However, several families were poorly represented in our data set, so we used order-based predictions whenever the number of species within a family was less than 5. We did not estimate any reproductive traits for species whose order was represented by fewer than 3 species.

Table F1: Summary statistics for linear regression models used to estimate missing species reproductive traits.

Model	Multiple R2	F-statistic	Degrees of Freedom	Residual Std. Err.	P-value
LnAFR - Family	0.856	16.333	854	0.262	1.65E-86
LnAFR - Order	0.674	28.464	1086	0.349	1.56E-55
LnML - Family	0.752	8.408	841	0.363	3.60E-123
LnML - Order	0.560	16.952	1065	0.430	2.49E-100
LnLS - Family	0.941	44.194	940	0.363	6.33E-117
LnLS - Order	0.862	91.975	1196	0.491	6.07E-75
LnLPY - Family	0.665	3.906	546	0.356	2.30E-22
LnLPY - Order	0.330	4.762	746	0.431	2.12E-16

Appendix G: BIC model selection for analysis of species sensitivity

We used a multi-step model selection process to find an optimal model. Tables G1 through G8 present the top 5 models from each of these steps. Candidate sets included models generated with randomized variable combinations using the genetic algorithm of package glmulti (Calcagno 2014). Only logical combinations of variables and interactions were considered by excluding combinations with no biological meaning based on a synthetic review of literature on species sensitivity (e.g., Appendix D). For instance, size of geographic range and litter size are both biologically meaningful correlates of species sensitivity, and models including them as main effects were thus considered. However, models containing an interaction between range extent and litter size were excluded from consideration, because there is no biological rationale for why litter size should be correlated with range size in a way that informs our understanding of species sensitivity to disturbance.

Within each candidate set, only fixed effects were changed between models. All models contained patch size (PLnPSize) and taxonomic class (TC) as fixed effects, and a categorical random variable specifying their citation (CiteID) to control for inter-study variation. The combination of these three key variables is hereafter referred to as the 'Base Model'. Confidence sets were defined as all models having a BIC value within 10% of the top model. Variables identified in each step were retained in the subsequent models if their summed BIC weights across the confidence set exceeded 0.5. The resulting final model, including all important variables and interactions identified at each step is presented in Equation G1 (variable codes presented in Table 1 of Chapter 3):

$$\begin{gathered}
\textit{Presence within Patch} \sim (1|CiteID) + PLnPSize + TC + \\
LHSt + LLnLandSize + LLnLandImp + SDC + SHSp + SLnBM + \\
RLnLS + RLnLPY + RLnML + LHSt{:}PLnPSize + TC{:}SHSp + \\
SDC{:}RLnLPY + TC{:}RLnLS + TC{:}SLnBM + TC{:}PLnPSize + \\
PLnPSize{:}SHSp + PLnPSize{:}RLnLS + PLnPSize{:}RLnML + \\
PLnPSize{:}SLnBM + SHSp{:}LLnLandImp + RLnLS{:}LLnLandImp + \\
SDC{:}LLnLandImp
\end{gathered} \qquad \text{Equation G1}$$

Table G1. Top five models exploring first order effects of landscape variables. All landscape variables were investigated in the candidate set, and all candidate models included the Base Model, as well as species name as a random variable. The confidence set consisted of a single model, so all variables present in this model were retained in subsequent steps.

Mod Num	Model	K	Log Likeli-hood	BIC	BIC weight	Confi-dence Set
1	LHSt+LLnLandSize+LLnLandImp	8	-27212	54513	0.942	TRUE
2	LHSt+LLnLandSize+LLnLandImp+LLnFragTime	9	-27210	54519	0.057	FALSE
3	LHSt+LLnLandSize+LLnPatches+LLnLandImp+LLnFragTime	10	-27210	54530	0.000	FALSE
4	LMatrix+LHSt+LLnLandSize+LLnLandImp	10	-27210	54530	0.000	FALSE
5	LMatrix+LHSt+LLnLandSize+LLnLandImp+LLnFragTime	11	-27208	54537	0.000	FALSE

Table G2. Top five models exploring interactions between landscape variables. First order terms of landscape variables retained from Table G1 were investigated. All candidate models included the Base Model and species name as a random variable. The confidence set consisted of a single model, so all variables present in this model were retained in subsequent steps.

Mod Num	Model	K	Log Likeli-hood	BIC	BIC weight	Confi-dence Set
1	LHSt+LLnLandSize+LLnLandImp+LHSt:PLnPSize	10	-26990	54090	0.971	TRUE
2	LHSt+LLnLandSize+LLnLandImp+LHSt:PLnPSize+ LLnLandSize:LLnLandImp	11	-26987	54097	0.029	FALSE
3	LHSt+LLnLandSize+LLnLandImp+LHSt:PLnPSize+ LHSt:LLnLandSize	12	-26989	54110	0.000	FALSE
4	LHSt+LLnLandSize+LLnLandImp+LHSt:PLnPSize+ LHSt:LLnLandImp	12	-26989	54110	0.000	FALSE
5	LHSt+LLnLandSize+LLnLandImp+LHSt:PLnPSize+ LHSt:LLnLandSize+LHSt:LLnLandImp	14	-26988	54130	0.000	FALSE

Table G3. Top five models exploring first order effects of species variables. All species variables were investigated in the full model set. All candidate models included the Base Model and terms identified in previous steps. The confidence set consisted of a single model, so all variables present in this model were retained in subsequent steps.

Mod Num	Model	K	Log Likeli-hood	BIC	BIC weight	Confi-dence Set
1	SDC+SHSp+SLnBM+SLnSArea+RLnLS+RLnLPY+RLnML	21	-30829	61888	0.991	TRUE
2	SDC+SHSp+SLnBM+RLnLS+RLnLPY+RLnML	20	-30840	61899	0.004	FALSE
4	SDC+SHSp+SLnBM+RLnAFR+RLnLS+RLnLPY+RLnML	21	-30835	61900	0.003	FALSE
3	SDC+SHSp+SLnBM+SLnSArea+RLnLS+RLnML	20	-30840	61900	0.002	FALSE
5	SDC+SHSp+SLnBM+SLnSArea+RLnAFR+RLnLS+RLnML	21	-30839	61909	0.000	FALSE

Table G4a. Top five models exploring interactions between species variables. First order terms of species variables retained from Table G3 were investigated. All candidate models included the Base Model and terms identified in previous steps. The confidence set consisted of multiple models, so we evaluated summed BIC weights over those models to assess variable retention for subsequent steps (Table G4b).

Mod Num	Model	K	Log Likeli-hood	BIC	BIC weight	Confi-dence Set
1	SHSp+SDC+SLnBM+RLnLS+RLnML+RLnLPY+TC:SHSp+ SDC:RLnLPY+TC:RLnLS+TC:SLnBM	34	-30440	61254	0.574	TRUE
2	SHSp+SDC+SLnBM+RLnLS+RLnML+RLnLPY+TC:SHSp+ SDC:RLnLPY+TC:RLnLS+SDC:SLnBM	33	-30446	61255	0.426	TRUE
3	SHSp+SDC+SLnBM+RLnLS+RLnML+RLnLPY+TC:SHSp+ TC:SDC+SDC:RLnLPY+TC:RLnLS	35	-30462	61308	0.000	FALSE
4	SHSp+SDC+SLnBM+RLnLS+RLnML+RLnLPY+TC:SHSp+ SDC:RLnLS+SDC:RLnLPY+TC:RLnLS	33	-30479	61319	0.000	FALSE
5	SHSp+SDC+SLnBM+RLnLS+RLnML+RLnLPY+TC:SHSp+ SHSp:SLnBM+SDC:RLnLPY+TC:RLnLS	33	-30481	61325	0.000	FALSE

Table G4b. Summed BIC weights for the confidence set identified in Table G4a.

	Term											
	SHSp	SDC	SLnBM	RLnLS	RLnML	RLnLPY	SLnS Area	TC: SHSp	SDC: RLnLPY	TC: RLnLS	TC: SLnBM	SDC: SLnBM
Model 1 BIC Wt.	0.574	0.574	0.574	0.574	0.574	0.574	0.000	0.574	0.574	0.574	0.574	0.000
Model 2 BIC Wt.	0.426	0.426	0.426	0.426	0.426	0.426	0.000	0.426	0.426	0.426	0.000	0.426
Summed BID Wt.	1.000	1.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000	0.574	0.426
Term Retained	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	NO

Table G5. Top five models exploring interactions between the species component of the Base Model (i.e., taxonomic class; TC) and previously identified landscape variables. All candidate models included the Base Model and all terms identified as important in previous steps. The confidence set consisted of a single model, which identified a single interaction term that was retained in subsequent steps.

Mod Num	Model	K	Log Likeli-hood	BIC	BIC weight	Confi-dence Set
1	TC:PLnPSize	37	-31857	64123	1.000	TRUE
2	PLnPSize:TC + LLnLandImp:TC	40	-31855	64151	0.000	FALSE
3	PLnPSize:TC + LLnLandSize:TC	40	-31856	64153	0.000	FALSE
4	LHSt:TC + PLnPSize:TC	41	-31854	64160	0.000	FALSE
5	*No additional terms*	34	-31899	64173	0.000	FALSE

Table G7a. Top five models exploring of interactions between the landscape component of the Base Model (i.e., patch size; PLnPSize) and previously identified species variables. All candidate models included the Base Model and terms identified as important in previous steps. The confidence set consisted of multiple models, so we evaluated summed BIC weights over those models to assess variable retention for subsequent steps (Table G7b).

Mod Num	Model	K	Log Likeli-hood	BIC	BIC weight	Confi-dence Set
1	PLnPSize:SHSp+PLnPSize:RLnLS+PLnPSize:RLnML+ PLnPSize:SLnBM	42	-31805	64073	0.816	TRUE
2	PLnPSize:SHSp+PLnPSize:RLnML	40	-31818	64077	0.113	TRUE
3	PLnPSize:SHSp+PLnPSize:RLnLS+PLnPSize:RLnML	41	-31813	64078	0.065	FALSE
4	PLnPSize:SHSp	39	-31827	64083	0.005	FALSE
5	PLnPSize:SHSp+PLnPSize:RLnLS	40	-31823	64087	0.001	FALSE

Table G7b. Summed BIC weights for the confidence set identified in Table G7a.

	Term			
	SHSp	**RLnLS**	**RLnML**	**SLnBM**
Model 1 BIC Weight	0.878	0.878	0.878	0.878
Model 2 BIC Weight	0.122	0.000	0.122	0.000
Summed BID Weight	1.000	0.878	1.000	0.878
Term Retained	YES	YES	YES	YES

Table G8a. Top five models exploring interactions between previously identified landscape and species variables. All candidate models included the Base Model and terms identified as important in previous steps. The confidence set consisted of multiple models, so we evaluated summed BIC weights over those models to assess variable retention for the final model (Table G8b).

Mod Num	Model	K	Log Likeli-hood	BIC	BIC weight	Confi-dence Set
1	RLnLS:LLnLandImp+SDC:LLnLandImp+SHSp:LLnLandImp	47	-31756	64030	0.832	TRUE
2	RLnLS:LLnLandImp+SDC:LLnLandImp	45	-31769	64034	0.167	TRUE
3	RLnLS:LLnLandImp+LLnLandSize:RLnLS+SDC:LLnLandImp	46	-31768	64044	0.001	FALSE
4	RLnLS:LLnLandImp+SDC:LLnLandImp+SDC:LLnLandSize	47	-31764	64046	0.000	FALSE
5	RLnLS:LLnLandImp+LLnLandSize:RLnLS+SDC:LLnLandImp+SDC:LLnLandSize	48	-31763	64056	0.000	FALSE

Table G8b. Summed BIC weights for the confidence set identified in Table G8a.

	Term		
	RLnLS: LLnLandImp	SDC: LLnLandImp	SDC: LLnLandSize
Model 1 BIC Weight	0.833	0.833	0.833
Model 2 BIC Weight	0.167	0.167	0.000
Summed BID Weight	1.000	1.000	0.833
Term Retained	YES	YES	YES

Appendix H: Results of analysis exploring the potential impact of phylogeny

Phylogeny may (Bradshaw et al. 2014) or may not (Newbold et al. 2013) impact the results of studies that investigate how species characteristics predict factors such as sensitivity to disturbance. Quantitatively accounting for phylogeny was particularly problematic in our analysis, because a well-resolved phylogeny that is consistent across all four taxonomic classes (i.e., amphibian, bird, mammal, and reptile) is not currently available. In order to evaluate the potential impact of phylogeny in the results of Chapter 3, we re-ran the optimal model (Appendix G) with the addition of taxonomic family, nested within class, as a random variable, and compared results to the original model (Table H1).

Results are highly similar across models, and incorporation of additional taxonomic data does not affect any conclusions of our study. The main difference between models with and without additional taxonomic complexity is that effect size and significance for levels of taxonomic class and its interactions are reduced. This result is expected, since we are providing additional information nested within class with which to fit the model, thus reducing the amount of variability explainable by class alone. The only term that is significant in either model, and also changes sign, is one level of diet. Specifically the effect of herbivory changes from weakly negative to non-significantly positive when family is included. Herbivory is a taxonomically conserved trait, so this is understandable, and moreover, we do not make inference to the effects of herbivory in this study, so a slight difference in this trait does not change any conclusions in our paper.

Table H1. Effect size and significance level for fixed terms in models with and without family-level taxonomic information included as a random variable. Variable codes are explained in Table 1 of Chapter 3. Significance noted as: *** = P < 0.001, ** = P < 0.01, * = P < 0.05.

	Model without Family		Model with Family	
Term	**Estimate**	**Significance**	**Estimate**	**Significance**
Intercept	0.59		0.16	
PLnPSize	0.39	***	0.36	***
TCA	-2.69	***	-2.36	***
TCM	-1.54	***	-0.77	*
TCR	-0.55	**	-0.32	
LHStGrass	0.22		0.39	
LHStShrub	0.61	*	0.65	*
LLnLandSize	-0.34	***	-0.35	***
LLnLandImp	-0.13	*	-0.20	***
SDCC	-0.91	***	-0.55	***
SDCH	-0.19	*	0.08	
SHSp1	-0.87	***	-0.96	***
SHSp2	-0.14		-0.35	***
SLnBM	-0.25	***	-0.28	***
RLnLS	-0.30	***	-0.18	**
RLnLPY	0.18	***	0.19	**
RLnML	0.64	***	0.56	***
PLnPSize:LHStGrass	-0.29	***	-0.30	***
PLnPSize:LHStShrub	-0.08	**	-0.08	*
TCA:SHSp1	1.56	***	1.40	***
TCM:SHSp1	0.37	***	0.36	**
TCR:SHSp1	0.63	***	1.06	***
TCA:SHSp2	-0.33	**	-0.37	**
TCM:SHSp2	0.56	***	0.56	***
TCR:SHSp2	-0.18		-0.44	***
SDCC:RLnLPY	0.09		0.06	
SDCH:RLnLPY	-0.54	***	-0.71	***
TCA:SLnBM	-0.19	***	-0.21	***
TCM:SLnBM	0.15	***	0.08	*
TCR:SLnBM	0.21	***	0.30	***
TCA:RLnLS	0.54	***	0.55	***
TCM:RLnLS	0.85	***	0.67	***
TCR:RLnLS	-1.01	***	-1.22	***
PLnPSize:TCA	-0.04		-0.05	
PLnPSize:TCM	0.00		0.02	
PLnPSize:TCR	0.21	***	0.23	***
PLnPSize:SHSp1	0.07	***	0.07	***
PLnPSize:SHSp2	0.00		0.01	
PLnPSize:RLnLS	-0.01		-0.01	
PLnPSize:RLnML	-0.05	***	-0.03	***
PLnPSize:SLnBM	0.01	***	0.01	***
LLnLandImp:RLnLS	-0.03	***	-0.01	
LLnLandImp:SDCC	-0.10	***	-0.07	***
LLnLandImp:SDCH	-0.09	***	-0.06	***
LLnLandImp:SHSp1	-0.04		-0.08	***
LLnLandImp:SHSp2	0.05	**	0.01	

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