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An Integrated Sampling and Analysis Approach for Improved Biodiversity Monitoring

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Abstract Successful biodiversity conservation requires high quality monitoring data and analyses to ensure scientifically defensible policy, legislation, and management. Although monitoring is a critical component in assessing population status and trends, many governmental and non-governmental organizations struggle to develop and implement effective sampling protocols and statistical analyses because of the magnitude and diversity of species in conservation concern. In this article we describe a practical and sophisticated data collection and analysis framework for developing a comprehensive wildlife monitoring program that includes multi-species inventory techniques and community-level hierarchical modeling. Compared to monitoring many species individually, the multi-species approach allows for improved estimates of individual species occurrences, including rare species, and an increased understanding of the aggregated response of a community to landscape and habitat heterogeneity. We demonstrate the benefits and practicality of this approach to address challenges associated with monitoring in the context of US state agencies that are legislatively required to monitor and protect species in greatest conservation need. We believe this approach will be useful to regional, national, and international organizations interested in assessing the status of both common and rare species.

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Introduction

Successful biodiversity conservation requires consistent, long-term monitoring data on species status and distribution. Gaps in data availability and quality can prevent accurate reporting on the condition of ecological systems and hinder identification of biodiversity hotspots (e.g., Yesson and others 2007), limiting capacity for informed decision-making and effective conservation planning (The Heinz Center 2006). Lack of data may seriously inhibit the ability to accurately classify the threat of extinction for many species. A recent report from the International Union for Conservation of Nature suggests that researchers have been able to classify the extinction threat for only 15% of the world's known mammals (Schipper and others 2008).

Worldwide, many organizations aim to monitor regional and local biodiversity in an effort to identify conservation priorities and assess management actions. Monitoring for conservation can be challenging because adequately estimating abundance, occurrence, or species richness can be hampered by large geographic areas or problems with imperfect detection of species (Yoccoz and others 2001; MacKenzie and others 2006; Kéry and Schmidt 2008). Many state and federal agencies have struggled to identify inexpensive yet efficient sampling and analysis tools that will assess quantitatively the status and distribution of key species. As a result, conservation priorities and management actions are not well-informed by available data.

In the United States (U.S.), traditional funding sources, such as the federal Pittman-Robertson Wildlife Restoration Act (§ 669) and statewide hunting license fees, have supported advances in population monitoring and successful conservation of game species over the last 85 years. Although non-game species account for almost 85% of the vertebrate diversity found in the U.S. (The Fish and Wildlife Conservation Act of 1980, P.L. 96-366, 94 Stat. 1322), limited funding for research and management has slowed progress in developing comprehensive approaches to non-game biodiversity monitoring. However, in 2001, the U.S. Congress passed the State Wildlife Grants Program (SWG), an initiative that provides federal funding for every U.S. state and territory to implement conservation programs benefiting species in greatest conservation need (SGCN), in an effort to keep species off of the Endangered Species List (Oberbillig 2008). Although the definition of a SGCN varies by state, most species included are threatened by habitat loss, invasive species, climate change, or contaminants (Oberbillig 2008). To receive federal appropriations, states must explicitly address the status and distribution of SGCN and how these species will be monitored over time. Although this legislation offers exciting opportunities for biodiversity conservation, state agencies may struggle with developing monitoring plans for numerous taxa, each with varying life history and habitat requirements. For example, the states of Florida, New York, and South Carolina have collectively identified over 2,800 fish, mammal, bird, amphibian, reptile, and invertebrate species in greatest conservation need (Fig. 1). The diversity and sheer abundance of species can make population-specific monitoring difficult, if not impossible, for a single agency. In addition, species of conservation value are often rare or elusive and thus present additional challenges for estimating population status over time, as data are often limited (MacKenzie and others 2005).

Recent statistical advances in community modeling (Dorazio and Royle 2005, Dorazio and others 2006) offer an innovative way to implement comprehensive biodiversity monitoring. This approach is based on hierarchical (or multi-level) models that allow for both improved estimates of individual species occurrences (including rare or infrequently observed species) based on landscape factors as well as an increased understanding of the aggregated response of a community to habitat heterogeneity. In this paper we outline the sampling methodology and basic analysis framework for implementing a comprehensive approach to biodiversity monitoring. As a case study, we focus on the application of hierarchical modeling for state monitoring of biodiversity as required by the State Wildlife Grants Program. However, we believe that the community-level framework is applicable for monitoring wildlife in any region, and provides a more efficient sampling and modeling methodology for tackling challenging population

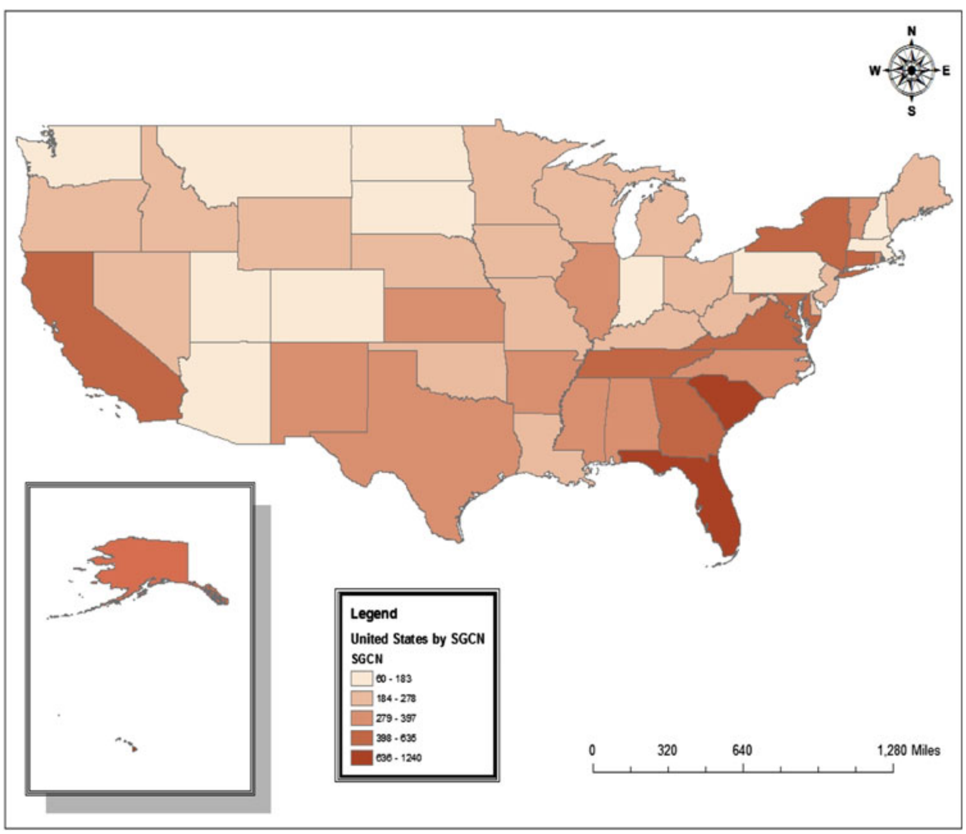

Fig. 1 Number of Species in Greatest Conservation Need (SGCN) in the United States by state, as identified in the State Wildlife Action Plans (http://www.wildlifeactionplans.org/). The figure includes mammals, birds, amphibians, reptiles, fish, and some invertebrates (e.g., freshwater bivalves, land snails, and crustaceans). Because insects were identified irregularly they were excluded from this analysis

estimation issues. Implementation of this monitoring strategy in a conservation setting can improve our understanding of the habitat and landscape needs of important wildlife communities, especially for rare and threatened species in which traditional monitoring techniques do not provide enough information for effective analysis and management.

The U.S. State Wildlife Grants Program

The goal of SWG is to provide states with federal money to protect and conserve nongame species. To receive federal funding through SWG, Congress mandated that each state develop a comprehensive state wildlife action plan (SWAP) that addresses the following eight elements:

(1) Information on the distribution and abundance of wildlife
(2) Descriptions of locations and relative conditions of essential habitats
(3) Descriptions of problems that may adversely affect species or their habitats, research priorities and survey efforts.
(4) Descriptions of conservation actions proposed to conserve the identified species and habitats.
(5) Plans for monitoring species and habitats, conservation actions, and for adapting these conservation actions to respond to new information.
(6) Descriptions of procedures to review the plan at intervals not to exceed 10 years.
(7) Coordination with federal, state, and local agencies and Indian tribes in developing and implementing the wildlife action plan.
(8) Broad public participation in developing and implementing the wildlife action plan.

(Fiscal Year 2001 Commerce, Justice, State and Related Agencies Appropriations Act, Public Law 106–553, codified at U.S. Code 16 (2000) 669(c)).

These criteria were identified as the primary components for conservation success (Oberbillig 2008), and serve as the foundation for long-term funding of non-game species management. Given the large number of SGCN, their varying life histories, and limited state agency budgets and personnel, developing a wildlife action plan that addresses the conservation needs of each species is a daunting task.

Designing and implementing a comprehensive monitoring program (element 5) for SGCN and their habitats will be particularly challenging for most states. Because the information needed to assess accurately population status and distribution (elements 1 and 2) can be costly to obtain, high quality data on important wildlife may be limited. Though states often focus monitoring and assessment efforts on individual—frequently charismatic—species, it is not practical or feasible to develop monitoring protocols for each SGCN. For example, in an effort to tackle the complexity of developing monitoring programs for multiple habitats and species, the Nevada Department of Wildlife developed a list of candidate SGCN indicators of habitat quality and dependence that will be targeted for long-term monitoring efforts (Murphy and others 2009). Although Murphy and others (2009) offer a well-devised approach to monitor individual species and their relationship to priority habitats, the use of indicators relies on assumptions that need to be explicitly tested. Species that have been overlooked for monitoring and analysis could be better indicators of habitat quality or could be more sensitive to critical threats in a way that was previously unknown, particularly as climate change interacts synergistically with other threats to reshape the landscape in novel ways.

If the challenges of developing a wildlife monitoring program are approached by sampling groups of species based on their taxon or life history characteristics, we can use multi-species based monitoring and analysis methods to more accurately and efficiently estimate the occurrence status of both target and non-target SGCN communities. This approach would fit well with the habitat and ecosystems-based approach that most states have adopted to organize conservation actions, and would allow agencies to continuously assess priorities, test assumptions about wildlife-habitat relationships, and create a flexible framework to track the population status of multiple species. The integrated community-level approach also addresses the monitoring and assessment elements of the SWAP (1, 2, and 5) for multiple species, which will lead to more effective conservation actions (elements 4 and 6) for wildlife communities as a whole.

Community-Level Monitoring Methods

Data Collection Framework

Information about presence/absence of a species is widely used as a surrogate for direct information about abundance. Estimating occupancy is often less expensive than estimating the total abundance of a population and has been successfully used to determine species preferences for relevant habitat characteristics and the impacts of disturbance (e.g., Blair 1996). Current research has demonstrated that occurrence estimates for birds (Nichols and others 1998, 2000), amphibians (Bailey and others 2004), and mammals (MacKenzie 2006), that do not account for imperfect detection during sampling are negatively biased, and can lead to misinformed management or policy actions. Failure to account for imperfect detection leads to underestimating species occurrences and distributions as well as biased estimates in relationships between occurrence and habitat features (Gu and Swihart 2004). An individual may go undetected in an occupied sampling unit if it fails to call or leave signs that are visible or audible during data collection (MacKenzie and others 2006). Data that includes repeated visits within a period during which a population remains constant (e.g., a sampling season) yields a history of detections and non-detections (1's and 0's) providing the necessary information to estimate the "detectability" of the species of interest. Detection/non-detection surveys are now widely recommended as an appropriate alternative to simple presence/absence and abundance surveys, and are currently implemented in monitoring efforts for a number of taxa, including frogs and toads (Weir and others 2005), marsh birds (Nadeau and others 2008), and large mammals (Zielinski and Stauffer 1996; Karanth and Nichols 2002).

Traditional monitoring programs often have focused on estimating either occurrence or abundance for a single species of conservation importance, such as the Spotted Owl (*Strix occidentalis*) (e.g., Lint 2005) or Bald Eagle (*Haliaeetus leucocephalus*) (e.g., Smith and Clark 2007). Although this approach is practical when there is only one population of interest, the sheer number and diversity of species and habitats makes single-species monitoring unrealistic on a large scale. Given the current threats to biodiversity worldwide, and the recent legislative impetus for monitoring numerous SGCN, a single species data collection or analysis framework may be obsolete if not negligent. As an alternative, a multi-species sampling design offers a practical approach for collecting monitoring data on groups of similar species at the same time, across large or diverse regions. Such techniques maximize data collection per field effort by implementing standardized detection/non-detection surveys, which detect signals from multiple species at the same time (Manley and others 2004). This data collection approach has been similarly applied in aquatic systems when identifying biocriteria for stream integrity (e.g. Karr and Chu 1999) and is currently being implemented in the Environmental Protection Agency's long-term Monitoring and Assessment Program (EMAP) for aquatic ecosystems (McDonald 2002). Manley and others (2005) demonstrated the value of applying multi-species inventory techniques in terrestrial systems, and found that a series of concurrent bird, mammal, amphibian, and reptile surveys yielded detections for 89% of expected species in the study region. Though this approach may not be ideal for some extremely rare, secretive, or patchily distributed species, Manley and others (2005) found that the techniques provided population data for a large number and wide variety of vertebrate wildlife.

Combining multi-species inventory techniques with an integrated community-level hierarchical analysis will lead to an efficient way of obtaining improved occurrence estimates for all species within a taxon. The field data required for hierarchical modeling are similar to those of any statistically rigorous monitoring program and include the following: (1) detection/non-detection data with replicate samples (i.e., multiple surveys of sample units), (2) census techniques that detect multiple species at a given location, and (3) a statistical sampling design such as random or stratified random sampling. Although implementing a program with these requirements can be challenging, failure to do so may lead to biased estimates of population status (Yoccoz and others 2001) and erroneous conclusions about the conservation actions needed to protect important species. Sampling must occur in a probabilistic framework to accurately monitor population status (Schaeffer and others 1990, Thompson and others 1998). Simple or stratified random sampling designs can be generated using current geographic information systems (GIS) technology, and easily modified to meet the natural history requirements of target species and communities (e.g. stratified by cover for habitat specificity) (Heyer and others 1994), or to ensure a spatially balanced sample (e.g. generalized random tessellation stratified GRTS) (Stevens and Olsen 2004).

To satisfy the conditions of the SWAP, states that have a large percentage of privately owned land (e.g. New York, 90%; Smith and others 2001) will need to incorporate sampling locations on private as well as public areas. Though time consuming, this approach has been implemented successfully by monitoring efforts such as the Forest Inventory and Analysis (The Forest Inventory and Analysis National Program (FIA) 2009) and National Marsh Bird Monitoring (Conway 2008) programs. Additionally, it offers an opportunity to engage with, and educate, local citizens on the importance of conserving biodiversity on their property.

Analysis Framework

The theory and technique of community-level hierarchical modeling, which assesses community composition through estimation of individual species occurrences, was developed in Dorazio and Royle (2005) and Dorazio and others (2006). The fundamental idea is that species-specific detection and occurrence estimates can be improved using collective data from all species within a community that were observed during sampling. An advantage of the hierarchical modeling framework is that it accounts for both species-level effects as well as aggregated effects on the community as a whole (Kéry and Royle 2008, 2009), leading to a more efficient use of available data and increased precision in estimates of occupancy, especially for infrequently observed species. In the hierarchical community model, we assume that site-specific occupancy ("true" presence/absence) for each species i at site j, denoted $z_{i,j}$, is a Bernoulli random variable, $z_{i,j} \sim Bern(\psi_{i,j})$, where $\psi_{i,j}$ is the probability that species i occurs at site j. Since the state variable $z_{i,j}$ can not be observed perfectly, we use the repeated sampling protocol to formally distinguish between non-detection and absence for each species at each sampling location (MacKenzie and others 2006). In this framework, we observe data $x_{i,j,k}$ for species i at site j during sampling period k, which are also assumed to be Bernoulli random variables if species i is present (i.e., if $z_{i,j} = 1$) and is zero otherwise. The observation model is then $x_{i,j,k} \sim Bern(p_{i,j,k} \cdot z_{i,j})$ where $p_{i,j,k}$ is the detection probability of species i for the kth sampling period at site j, if species i is present at site j. Thus species detection is a fixed zero when that species does not occur (because $z_{i,j} = 0$ leading the probability that the species was observed equal to $p_{i,j,k} \cdot 0$). For example, if species i has a detection history of $\{001\}$ at location j, then we know that i was in fact present at j ($z_{i,j} = 1$) and the probability of such a detection history is $(1 - p_{i,j})(1 - p_{i,j})\, p_{i,j}$ where $p_{i,j}$ is the detection probability for species i at location j, which is assumed here to be constant across all three sampling events ($p_{i,j} = p_{i,j,k}$ for $k = 1, 2, 3$). Occurrence and detection are generally modeled on the logit scale to constrain the values to be from 0 to 1 (i.e., 0–100% occurrence/detection probability). In the simplest formulation $\text{logit}(\psi_{i,j}) = \alpha_i + \beta_j$ where α_i is a species effect and β_j is a location effect on occurrence for species i at location j (Dorazio and others 2006). Detection is modeled in a similar fashion. In this formulation it is straightforward to add either landscape-level characteristics (e.g., amount of available habitat, distance to urban areas, etc.) or sampling (e.g., date and time of survey) effects by adding them in the logit models of species occurrence and detection, respectively (Kéry and Royle 2009; Russell and others 2009). An equally important benefit of the community modeling approach is that it can be extended to estimate occupancy, including species persistence and colonization, over multiple time steps (Ruiz-Gutiérrez and others 2010; Kéry and others 2009). Since states have a need to assess the occupancy status of each SGCN over long time horizons, the inclusion of annual or decadal variation associated with occupancy should be a useful extension. Furthermore, the flexibility of the modeling framework can allow for sampling locations to vary over years (or for years with missing data; Ruiz-Gutiérrez and others 2010). Thus the community model can estimate species-specific detection and occurrence probabilities at various heterogeneous locations based on localized characteristics and incorporate relevant temporal dynamics.

The community component is incorporated into the model by assuming that, within a given taxa or community, each species' occurrence, detection, and covariate effects are related to those of other species through a common distribution. For example, we assume that the baseline occurrence of species i (α_i) is drawn from a single normal distribution such that $\alpha_i \sim N(\mu_\alpha, \sigma_\alpha)$, where μ_α is the mean occurrence probability across species (on the logit scale) and σ_α is the standard deviation of occurrence among species. By linking the individual species parameters, the data are utilized more efficiently leading to improved precision in species-specific estimates of occurrence, especially for rare or elusive species, which frequently cannot be estimated using single-species analyses (Zipkin and others 2009). The parameters in the model can be estimated using a Bayesian approach (Royle and others 2007) that is implemented in the freely available software programs R (http://www.r-project.org/) and WinBUGS (Spiegelhalter and others 2003). More details of the modeling process, including applications of the model, can be found in Royle and Dorazio (2008, Chap. 11), Kéry and Royle (2008), and Russell and others (2009), the previously mentioned articles, as well as a community modeling website that provides examples of various models (basic to complicated) and software code for implementing each model (http://www.mbr-pwrc.usgs.gov/pubanalysis/communitymodeling).

The hierarchical modeling framework results in the best possible estimates for all species given available data and improves understanding of both individual species occurrences and distributions as well as the aggregated response of the community to habitat heterogeneity. The community modeling approach has been successfully applied to communities of butterflies (Dorazio and others 2006) and birds (Kéry and Royle 2009) and could readily be applied to other taxa where data are available. Community modeling can offer benefits in assessing current status and habitat requirements, as well as long term dynamics with respect to conservation threats (Kéry and others 2009, Ruiz-Gutiérrez and others 2010). This approach is particularly valuable for state agencies, as well as other conservation organizations, that wish to monitor and maintain common species while exploring the conservation needs of rare, threatened, and endangered species.

Implications for Biodiversity Monitoring and Conservation

As conservation and government agencies struggle to monitor and protect important species, the multi-species inventory and hierarchical modeling approach offers a valuable tool that can efficiently and effectively achieve those objectives. Specifically it provides: (1) a cost-effective approach for monitoring multiple species, (2) improved estimates of occurrence status and distribution for both individual species and community assemblages, and in our example, (3) a scientifically defensible framework for addressing federal monitoring requirements of SGCN.

Wildlife managers and policy makers need the best available data and analytical tools to create scientifically defensible policy, legislation, and management. Through the SWG, U.S. government agencies have a unique opportunity to develop comprehensive monitoring efforts that will improve the management and conservation of non-game species. The integrated multi-species monitoring and hierarchical modeling framework that we presented provides a sophisticated yet practical way to track the status and distribution of important wildlife communities, and meet the federal requirements outlined in the SWG (completely addressing elements 1 and 5). This approach will be particularly useful for agencies that are updating their SWAPs to incorporate the impacts of climate change on wildlife and their associated habitats, and could be identified as a priority for improving our understanding of the long-term implications of climate variability on key communities.

Monitoring based on statistical sampling is necessary to ensure rigorous inferences about the conservation status of important species and to inform effective policy and management. In areas where large tracts of private land or remote locations make access challenging, a random sampling design may seem inefficient or impractical. While focusing research efforts on public property may be less problematic, over 60 % of the U.S. land is in private ownership (Lubowksi and others 2002). Ignoring private or remote areas in survey efforts may lead to erroneous conclusions about the true status of important species, and limit identification of high quality habitat that should be highlighted for conservation outreach or acquisition. While the sampling techniques under this framework may be demanding, the need for high quality biodiversity data and precise estimates of species status and trends is critical.

Advanced statistical modeling approaches may intimidate state agencies or NGO's that have limited staff or resources. However, recent publications (Dorazio and others 2006; Gelman and Hill 2006; Kéry and Royle 2008, 2009), freely available software, as well as affordable quantitative workshops geared towards applied conservation (e.g., http://www.proteus.co.nz/home.html) will facilitate learning these new methods. Similarly, successful community sampling efforts (rather than single species) demonstrate that this approach is not only possible but also practical once implemented (Weir and others 2005; Manley and others 2005; Nadeau and others 2008).

In the short term, multi-species monitoring and assessment will help provide scientifically defensible baseline estimates for understanding how species communities are distributed across heterogeneous landscapes. By coupling this approach with other habitat monitoring efforts at a local (e.g., patch) or regional (e.g., remote sensing) scale, we can improve our ecological understanding of the habitat covariates that promote species occurrences. In addition, the probabilistic sampling design allows the results of our proposed framework to be used for predictions about species occurrences at unknown locations (Zipkin and others 2009). For example, DeWan and others (2009) used estimates of occurrence for area-sensitive birds to prioritize conservation of forest fragments in a rapidly urbanizing region. This type of information will be useful to land use planners and wildlife managers interested in identifying areas that are predicted to support a great deal of biodiversity as well as understanding the trade-offs in species level occurrences associated with specific management actions (Russell and others 2009; Zipkin and others 2010).

In the long term, community-based sampling and analysis will improve our understanding of species distribution patterns and trends as the modeling framework can be extended to include colonization and extinction dynamics (Kéry and others 2009; Russell and others 2009; Ruiz-Gutiérrez and others 2010). In particular, a multi-species monitoring approach would allow conservation agencies to track the response of entire communities to complex stressors like climate change and habitat loss. As many organizations struggle to identify individual species that may be sensitive to these synergistic threats, a community approach could detect changes in the abundance or distribution of more common species that would have otherwise been overlooked (Zipkin and others 2009). Although we have demonstrated the value of implementing community-based sampling and analysis in terrestrial systems, the analytical framework could easily be applied to the multi-species data collected for aquatic systems such as EMAP. Currently the EMAP program analyzes data on multiple indicator species within a community. Applying the community analysis techniques we have identified could test underlying assumptions about the response of multiple species to given stressors, and uncover new relationships that may be important to ecosystem structure or function. Given the complexity of climate change and the variability in predicted impacts, a multi-species monitoring and analysis approach will enhance our ability to track and manage terrestrial and aquatic wildlife in the face of uncertainty.

The community-level approach is a useful framework for monitoring species at large scales because it uses available survey data in a statistically efficient manner. The precision of community and species level parameter estimates will necessarily be improved compared to single species analyses (Zipkin and others 2009). However, the quality of species occurrence estimates and the effects of habitat covariates will always depend on the amount of available data. Species that were observed infrequently will necessarily have larger confidence bounds around their occurrence estimates and will naturally be drawn towards community averages (Sauer and Link 2002). Thus analyses should include communities that are comprised of similar species (i.e., species whose responses to landscape heterogeneity could conceivably come from a common distribution). For the most useful results, species could be additionally grouped by characteristics of interest (e.g., habitat preference or behaviors) and incorporated into the model by assuming common distributions for species subsets rather than at the level of the whole community (Sauer and Link 2002).

As climate change, habitat loss, invasive species, and other threats continue to negatively impact biodiversity across the globe, it is imperative that conservation organizations identify the monitoring data needed to accurately assess species' status and trends. Although the magnitude and diversity of species makes conservation and management complex, a community level approach to data collection and analysis provides the fundamental conceptual framework for addressing these challenges.

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