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Review

A review of Bayesian belief network models as decision-support tools for wetland conservation: Are water birds potential umbrella taxa?

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ABSTRACT

Creative approaches to identifying umbrella species hold promise for devising effective surrogates of ecological communities or ecosystems. However, mechanistic niche models that predict range or habitat overlap among species may yet lack development. We reviewed literature on taxon-centered Bayesian belief network (BBN) models to explore a novel approach to identify umbrella taxa identifying taxonomic groups that share the largest proportion of habitat requirements (i.e., states of important habitat variables) with other wetland-dependent taxa. We reviewed and compiled published literature to provide a comprehensive and reproducible account of the current understanding of habitat requirements for freshwater, wetland-dependent taxa using BBNs. We found that wetland birds had the highest degree of shared habitat requirements with other taxa, and consequently may be suitable umbrella taxa in freshwater wetlands. Comparing habitat requirements using a BBN approach to build species distribution models, this review also identified taxa that may not benefit from conservation actions targeted at umbrella taxa by identifying taxa with unique habitat requirements not shared with umbrellas. Using a standard node set that accurately and comprehensively represents the ecosystem in question, BBNs could be designed to improve identification of umbrella taxa. In wetlands, expert knowledge about hydrology, geomorphology and soils could add important information regarding physical landscape characteristics relevant to species. Thus, a systems-oriented framework may improve overarching inferences from BBNs and subsequent utility to conservation planning and management.

1. Introduction

Biological conservation relies on identifying and connecting species with the habitat requirements important for the successful completion of life cycles. Species distribution models (SDMs) are increasingly relied upon to identify habitat elements important for conservation (Dibner et al., 2017; Phillips et al., 2017). Predictive SDMs are particularly needed for understanding how species will respond to ongoing environmental change (Wood et al., 2018). Increased access to, and advances in technology have improved our ability to understand associations between species and their habitats (Elith and Leathwick, 2009). Technological advances include Geographic Information Systems (GIS) and remote sensing technology, paired with increased computing power and the development of spatial statistical models (e.g., Guisan and Thuiller, 2005). Examples of this approach include Gap Analysis Program (GAP) models mapping land cover and predicted distributions of species, bioclimatic envelopes, habitat suitability indices, maximum entropy models (MAXENT), and genetic algorithm for rule-set prediction (GARP; Elith et al., 2006; Guisan and Zimmermann, 2000; Sowa et al., 2007). The results of SDMs are commonly used to build species-specific Habitat Suitability Indices (HSIs) that estimate the probability of species presence across a landscape and have been used extensively in conservation planning (Zajac et al., 2015). Thus, identifying the key elements of habitat for species of conservation concern is important for informing conservation actions (Lin et al., 2018).

Bayesian belief networks (BBNs) represent one form of SDM that offer a unique modeling approach by identifying explicit causal relationships among organisms and their habitats, as well as incorporating measures of uncertainty. In the ecological literature, BBNs go beyond species-habitat correlations because they explicitly consider discrete processes that influence occupancy across space and time (i.e., access and selection; Jones, 2001). BBNs consist of input, intermediate

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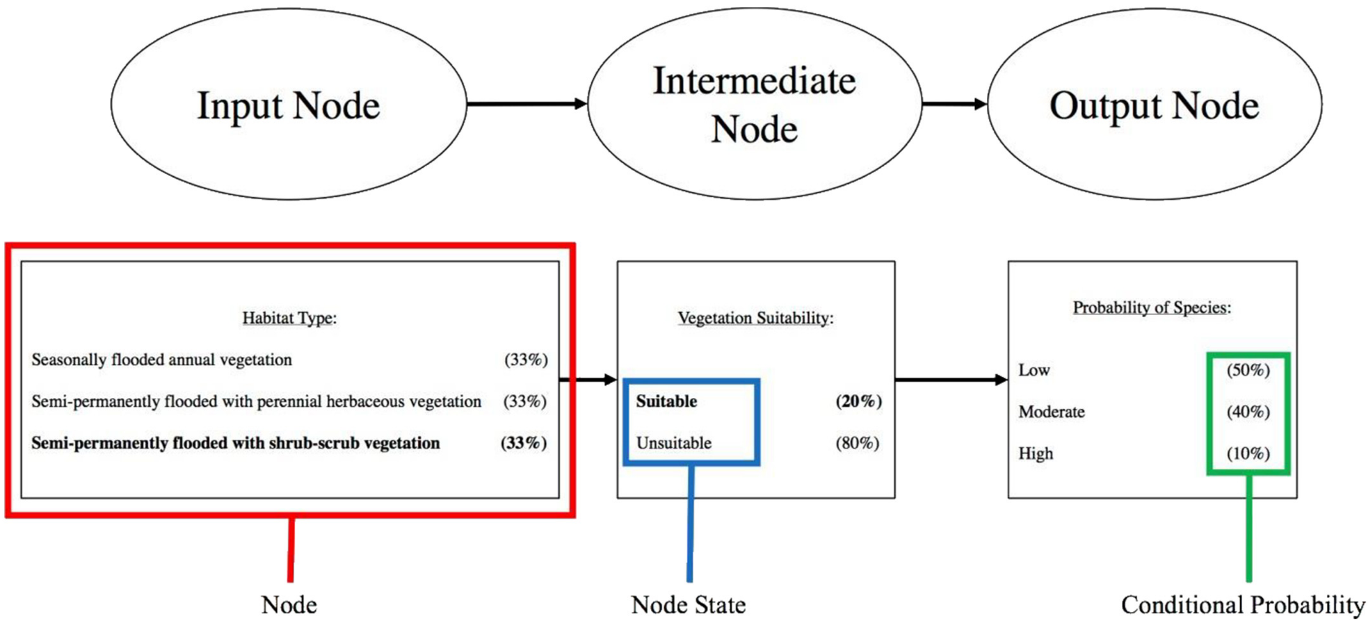

Fig. 1. An illustration of a simple Bayesian Belief Network (BBN). The links between input, intermediate and output nodes (ellipses) indicate a mechanistic relationship in the direction of the arrow (i.e., the state of the input node variable drives the state of the intermediate node variable etc.). Input nodes are defined by marginal (unconditional) probability distributions defined by the range of states found in nature. Intermediate and output nodes are defined by conditional probability tables, with the probability for the node being in a specific state given by the configuration of the states of "parent" nodes. In the bottom part of the figure we demonstrate a hypothetical landscape with equal probabilities of encountering each type of habitat. In bold we represent that where there is semi-permanently flooded habitat with shrub-scrub vegetation, there is a 20% probability of finding suitable habitat (intermediate node) for an imaginary taxa. As the habitat is suitable, there is a 50% probability that the chances of encountering one individual of the species is low, a 40% probability that the chances of encountering one individual of the species is moderate, and a 10% probability that the chances of encountering one individual of the species is high. In this simplistic example, we show that the range of the probability of encountering the species (output node) changes based on the state at the input node.

and output nodes that are linked together via conditional probability tables (CPTs) according to hypothesized causal relationships (Fig. 1; Drew and Collazo, 2014). As graphically based probabilistic models (i.e., influence diagrams), BBNs may incorporate information gleaned from literature reviews, expert opinions and monitoring efforts to examine how all possible values of environmental variables may influence the occurrence or distribution of individuals. Bayesian belief networks approach SDMs by exhaustively exploring potential ecological variables defining a species' niche while simultaneously incorporating metrics of uncertainty surrounding estimates of habitat requirements (Marcot et al., 2006; Uusitalo et al., 2015). The inclusion of measures of uncertainty is important as many conservation decisions must be made in the absence of complete information. Thus, a BBN modeling approach can be used to inform decisions made using an adaptive management approach to reduce uncertainty (Drew and Collazo, 2014).

The umbrella species concept (Wilcox, 1984) can enhance conservation for suites of species with similar habitat requirements by countering incomplete biodiversity surveys that lack time, financial support, or adequate methods. The umbrella species concept provides a framework to improve the effectiveness of conservation action while reducing the complexity of quantifying species-specific outcomes. Umbrella species are unique in that they represent an ecologically-defined role in conservation as managing for their life history needs is expected to serve other species that co-occur or rely on the same set of resources (Roberge and Agelstam, 2004). As such, umbrella species are habitat specialists with large ranges sizes, and that are often sensitive to environmental disturbance (Kalinkat et al., 2017). Creative approaches to identifying umbrella species hold promise for devising effective surrogates of ecological communities or ecosystems (Sattler et al., 2014), but mechanistic niche modeling for predicting overlap of species' ranges and habitat requirements can be developed by narrowing gaps in our understanding of species ecology (Kearney and Porter, 2009).

Efforts to quantitatively identify umbrella species from among multiple candidate taxa (Caro and O'Doherty, 1999; Fleishman et al., 2000; Maslo et al., 2016; Stewart et al., 2017) often focus solely on contrasting spatial overlap identified using potentially incomplete sets of environmental predictors (Andelman and Fagan, 2000; Seddon and Leech, 2008). Despite past mixed success of using umbrella species for conservation planning (e.g., successful: Fleishman et al., 2000; Roth and Weber, 2007; Suter et al., 2002, unsuccessful: Launer and Murphy, 1994; Ozaki et al., 2006), the concept continues to improve by broadening to encompass both taxonomic and functional diversity (Sattler et al., 2014). Typical approaches to identifying umbrella species have used SDMs that lacked explicit mechanistic reasoning to identify spatial ranges (i.e., beyond spatial overlap to encompass responses to similar environmental conditions) (Cayuela et al., 2009; Elith and Leathwick, 2009). As the umbrella approach to wider species conservation holds promise for identifying effective surrogate taxa (Sattler et al., 2014), we present a method to identify umbrella taxa informed by suites of BBN models that represent spatial ranges with causal reasoning.

Given the ability of BBNs to generate spatially-explicit predictions based on functionally-defined species-habitat relationships, they represent a potentially valuable approach to evaluate a species' expected performance as an umbrella species. Therefore, we took a case study and literature review approach to identify potential umbrella taxa within an ecosystem using BBN models. Restricting our research to freshwater wetland ecosystems, we undertook a systematic literature review to quantify the categorical overlap of habitat requirements for freshwater wetland-dependent species among existing BBNs. We reviewed existing taxon-centered BBN models to: 1) assess how BBNs were constructed, 2) describe how BBNs were used to inform biological conservation and identify the extent BBNs appeared to be used by those making biological conservation decisions, and 3) identify candidate umbrella taxa.

We chose freshwater wetlands because of the important role they