IMPROVING IMPERILED SPECIES MANAGEMENT THROUGH SPATIALLY-EXPLICIT DECISION TOOLS

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Abstract

Recovery plans for imperiled species have historically been based on untested assumptions, failing to acknowledge ecological uncertainty behind recovery goals and decisions. In order to acknowledge the many sources of uncertainty, imperiled species should be managed under a decision analysis framework. We created such a decision framework for management of the federally threatened blackside dace (*Phoxinus cumberlandensis*) by describing anthropogenic and ecological influences in a Bayesian belief network (BBN). The core network describes how measurable environmental variables influence habitat conditions and subsequently affect probability of local population persistence. This network was then attributed using publicly accessible spatial data for 52 local populations to determine probabilities of persistence for each local population. We then linked GIS (ArcGIS) and decision analysis software (Netica), allowing end-users to parameterize this network for individual populations and evaluate specific land management changes. Our BBN demonstrates that because population conditions and environmental gradients vary across the landscape, so do the likely effects of different land uses. Furthermore, variation in land ownership and jurisdiction results in suites of likely land management decisions that also vary spatially. Therefore our spatially-explicit decision framework may lead to near-optimal decision-making across the complete range of blackside dace.

Keywords. Bayesian belief networks, blackside dace (*Phoxinus cumberlandensis*), endangered species, decision analysis

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Introduction

Assuming that management decisions will have similar results when applied to geographically different locations ignores a large portion of ecological variability. Accounting for environmental and demographic variation in a spatially-explicit manner improves management decision making processes. Spatially-explicit species management requires two main components: local conditions (data) for individual locations and a universal model transferable across geographic space. We developed a model that provides unique results across geographic space to improve the recovery of a currently threatened species: the blackside dace (*Phoxinus cumberlandensis*).

Background

Few places in the world have freshwater fish assemblages as rich in species composition as the United States (Warren and Burr, 1994). The largest contribution to this richness comes from the southeastern region, which contains 62% of all freshwater fish species in the country (Warren et al., 1997). Disturbingly, a large proportion of these fish species are currently threatened with extinction (Warren et al., 1997). In fact, a recent survey classified 28.7% of southeastern freshwater fish as endangered, threatened, or vulnerable, a 125% increase over the previous 20 years (Warren et al., 2000).

Direct and indirect anthropogenic alteration of habitat is the basis for virtually all of the declining fish populations in the southeast (Warren et al., 1997; Warren et al., 2000). These alterations include, but are not limited to, physical changes to the landscape such as pollution inputs and extraction of resources (Kapustka, 2005; Munns, 2006; Warren et al., 2000), modification of metapopulation dynamics through fragmentation (Hanski et al., 1995, Hanski, 2004) and transformation of ecosystem properties through the introduction of non-native species (Canonico et al., 2005; Kolar and Lodge, 2002). Effective management of native aquatic ecosystems must recognize the cumulative effects of the stressors, while also heeding the possibility of interactions between them (Munns, 2006).

The Cumberland River drainage of Kentucky and Tennessee is a prime example of the conflict between human land use and native aquatic biota. This drainage is one of the southeastern region's richest in terms of overall native taxa and endemic taxa, while also being one of the highest in number and percent of imperiled taxa (Table 1) (Warren et al., 1997). The high imperilment of fish within this drainage is largely the result of a long history of unchecked human alteration of freshwater streams through impoundments and extractive land use such as logging, drilling, and mountain top mining (U.S. Fish and Wildlife Service, 1987).

This extractive land use has been cited as the primary cause of the decline in populations of the blackside dace, an imperiled native endemic (Starnes and Starnes, 1978). Formally described in 1978 by Starnes and Starnes, the blackside dace was listed as threatened under the Endangered Species Act in 1987 in response to known extirpation events and region-wide reduced habitat distribution (Mattingly and Contributors, 2005; Starnes and Starnes, 1978; U.S. Fish and Wildlife Service, 1987). Currently, the blackside dace is thought to inhabit approximately 105 unique streams (personal communication with Mike Floyd, U.S. Fish and Wildlife Service), but

Table 1. Aquatic community metrics for the Cumberland River drainage (Warren et al., 1997).

Aquatic community metric	Value	Rank[a]
Overall native taxa	147	4th
Number of unique taxa	15	2nd
Number of imperiled taxa[b]	19	1st (tie)
Percent of imperiled taxa	12.9%	1st

[a] Out of 33 southeastern watersheds
[b] Imperilment based on American Fisheries Society conservation status

the threat of further decline is imminent because land use practices continue to affect population survival at individual sites (Mattingly and Contributors, 2005; U.S. Fish and Wildlife Service, 1987).

The U.S. Fish and Wildlife Service instituted a recovery plan for the blackside dace that centers on the general goals of achieving population viability and protection. This document primarily requires the establishment of three protected, viable populations in eight sub-basins (U.S. Fish and Wildlife Service, 1988). Specifically, the document calls for no mining upstream of these viable populations and for mining practices close to these populations to allow for natural movement and colonization (U.S. Fish and Wildlife Service, 1988). The success of this recovery plan and consequently, the persistence of the blackside dace, centers on the validity of assumptions made about mining effects on the local scale (relating land use and population stability) and the metapopulation scale (24 populations constitute a stable metapopulation). As it stands, the recovery program is based largely on untested assumptions and goals.

Methods

We organized a group of blackside dace species experts and asked them to describe their own beliefs about ecological influences affecting blackside dace populations. These descriptions were open to any information derived from field experience, data collection, modeling, or the literature. We then constructed one comprehensive model by integrating all of the experts' knowledge into one framework. The resulting model provides a means of evaluating persistence of populations based on local land use conditions.

We selected the Bayesian belief network (BBN) modeling framework and employed the Bayesian network development software Netica version 3.25 (Norsys, 2007). BBNs are modeling tools used to depict the influence of ecological input variables on species response variables through probabilistic relationships (Marcot et al., 2006; Nyberg et al., 2006). We selected this modeling framework because it can employ different data types and sources, provides a useful communication tool, and can incorporate future monitoring data to update predictions based on new knowledge (Nyberg et al., 2006).

Model Development

We facilitated the creation of a BBN describing the dominant characteristics thought to influence blackside dace population responses (Figure 1). The model was developed over a four month period (December 2007 to March 2008) by a group of scientists and managers with extensive species knowledge (see acknowledgements). Initially, members filled out a questionnaire rating coarse (land use) and fine (habitat) scale threats and describing how these affect blackside dace populations. These responses were converted to an influence diagram or "ecological causal web" affecting blackside dace populations (Marcot et al., 2006). Broadly, the group selected six human land use inputs, four biological inputs, one environmental input, three watershed variables, four stream habitat variables, and three population parameters that cascade to influence the population response (Figure 1; Appendix A).

To convert this influence diagram into an initial BBN, each variable must be partitioned into discrete states by determining applicable monitoring units and biologically meaningful classes (Marcot et al., 2006). For example, summer stream water temperature was divided into two states: suitable (below 18.5° C) and elevated (above 18.5° C) based on recent research results (Jones, 2005) (Appendix A). Variables are now considered "nodes" within the BBN, with parent nodes influencing child nodes (Marcot et al., 2006). Member's beliefs about these discrete states were elicited through a second questionnaire.

Unique states for the population response node were designed to represent population trends over time. Local populations can grow (>10% increase), decline (>10% decrease), remain stable between these limits, or become locally extirpated. These responses are based on a 5-year time series because blackside dace life spans are approximately 3 to 4 years (Starnes and Starnes, 1978). Therefore a population with no reproduction could reasonably be expected to become locally extirpated in 5 years. We designed the BBN to be attributed with ecological variables at year zero but describe population response at year five to properly measure the prediction / response combination.

Parameterization of the BBN requires completing a conditional probability table (CPT) for each child node. CPTs contain conditional probabilities for each state of the child node for all combinations of parent node states (Table 2) (Marcot et al., 2006). Each member of the model development team parameterized CPTs based on their expert judgment of the system by filling out blank CPTs independently. These CPTs were then placed in a database and a single model CPT was created by averaging all individual responses.

Parentless nodes are not conditional upon other nodes and therefore use unconditional probability tables (Marcot et al., 2006). If analyzing over multiple populations, input (parentless) nodes would contain frequency tables, representing the relative frequency of each state of the node over the complete analysis set. However, for this analysis, we are only analyzing one population at a time. Therefore, the input nodes (human and biological inputs in Figure 1) will be attributed with known states (or a 100% frequency) for each population.

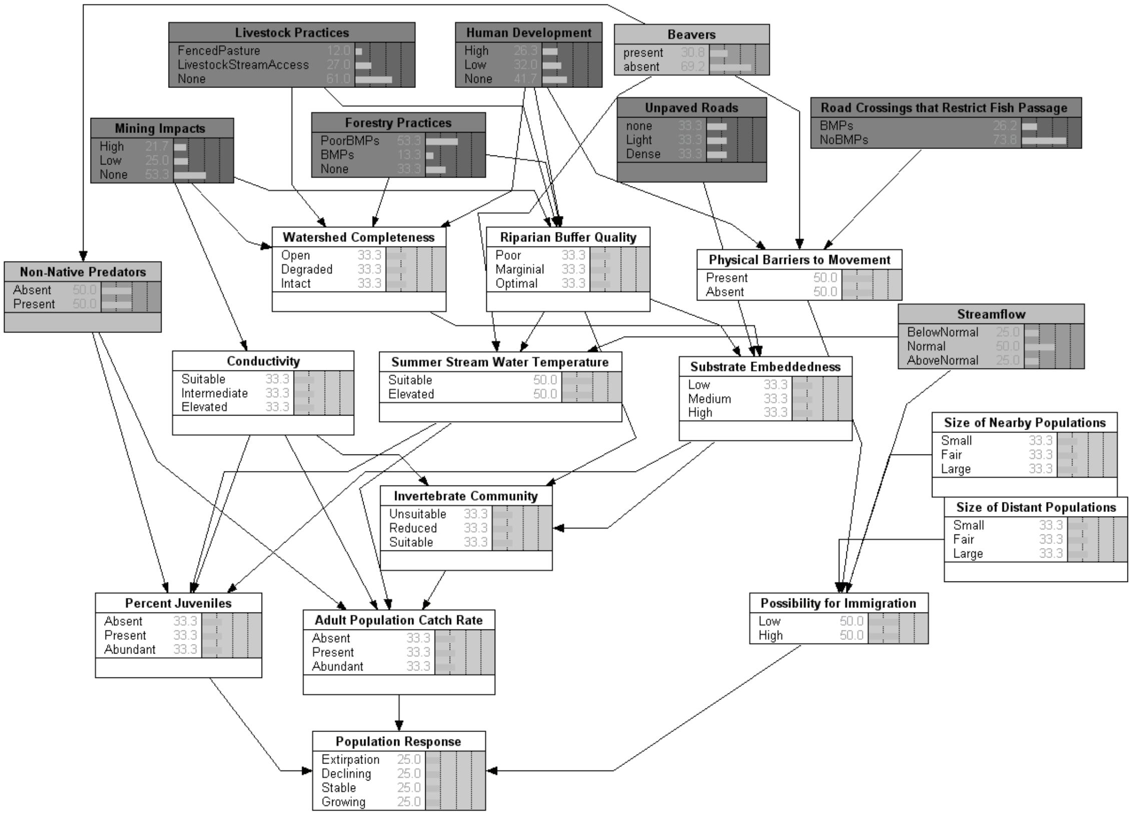


Figure 1. Bayesian belief network demonstrating the ecological influences on blackside dace population response. Overall model structure demonstrates that human (dark gray) and environmental (light gray) inputs influence ecological variables that shape the response of local blackside dace population response.

The group did discuss discrepancies in individual beliefs, but agreed that all responses should be given equal support. Debates concerning qualitative decisions (such as which variables to include in the BBN) were resolved through open discussion, while quantitative decisions (such as conditional probabilities) were resolved by averaging individual responses. Upon model completion, all members were satisfied with the model and supported its structure.

The primary input data for this model are human land use inputs (mining, urbanization, etc). In order to collect consistent input data for the entire study area, we calculated land use conditions using GIS software ArcGIS 9.2 (ESRI, 2005) (described in GIS Data Development section). We calculated these conditions within the watershed delineated upstream from population locations or "direct upstream watersheds." In order to link the modeling software and the data management software together, we created a geodatabase to store all applicable GIS and attribute data, and then developed a query tool within ArcGIS to display the data as an integrated and seamless application.

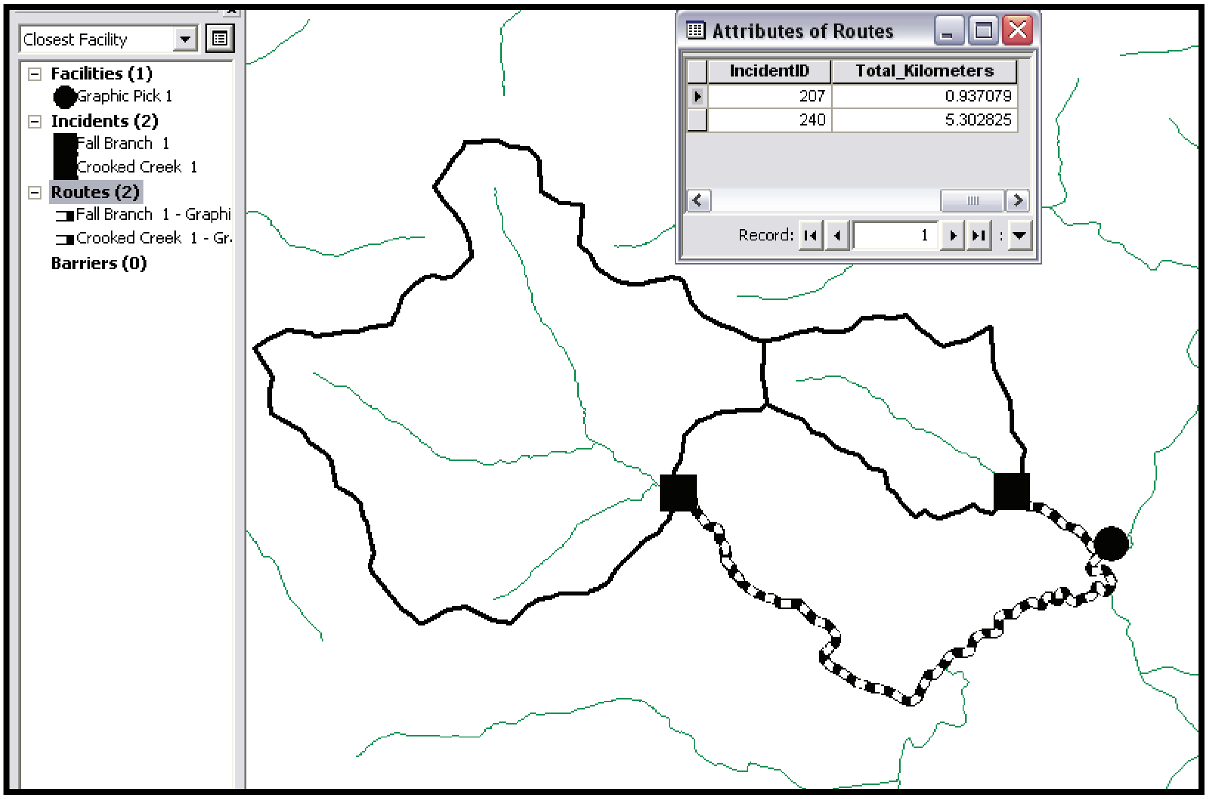
Table 2. Conditional probability table (CPT) for summer stream water temperature node.

Combination of parent node states			Probability of summer stream water temperature being in a particular state	
Streamflow	Riparian buffer quality	Beaver presence	Suitable	Elevated
Below normal	Poor	Present	9.4	90.6
Below normal	Poor	Absent	15.0	85.0
Below normal	Marginal	Present	23.4	76.6
Below normal	Marginal	Absent	31.0	69.0
Below normal	Optimal	Present	33.4	66.6
Below normal	Optimal	Absent	41.0	59.0
Normal	Poor	Present	35.0	65.0
Normal	Poor	Absent	44.0	56.0
Normal	Marginal	Present	43.0	57.0
Normal	Marginal	Absent	51.0	49.0
Normal	Optimal	Present	54.0	46.0
Normal	Optimal	Absent	64.0	36.0
Above normal	Poor	Present	53.0	47.0
Above normal	Poor	Absent	61.6	38.4
Above normal	Marginal	Present	58.8	41.2
Above normal	Marginal	Absent	66.0	34.0
Above normal	Optimal	Present	66.0	34.0
Above normal	Optimal	Absent	79.0	21.0

GIS Data Development

Spatially-explicit population analyses may be performed if input conditions are known for unique geographic locations. Therefore, we calculated land use conditions that described the input nodes for 52 unique, extant blackside dace population sites sampled between 2002 and 2005 in work submitted to the U.S. Fish and Wildlife Service (Mattingly and Contributors, 2005) by delineating unique watersheds for each sub-population. Land use GIS data within each unique watershed represent the influences upon a unique sub-population. Similarly, this data represent the input conditions for a BBN unique to the sub-population.

In order to analyze only the conditions directly affecting the location of interest, unique watershed polygons were created (Figure 2). Sample locations taken from Mattingly and Contributors (2005) were snapped to the appropriate stream reach in the National Hydrography Dataset (NHD) (U.S. Geological Survey, 2007) using route events in ArcMap software (ESRI, 2005). Direct upstream watersheds were delineated for each population site using the ArcHydro



IncidentID	Total_Kilometers
207	0.937079
240	5.302825

Figure 2. Visual description of GIS methods for two population locations. The hashed line represents the shortest stream route between the two streams. However, the first downstream junction (circle) must be included to calculate the correct distance. The distance from each population (shown as an incident in the network analyst window) to the junction (shown as a facility) is shown in the route attribute table.

Data Model (Maidment, 2002). First, streams were "burned" into a 10 meter digital elevation model (DEM) acquired from the U.S. Geological Survey, National Elevation Dataset (U.S. Geological Survey, 2005). The DEM was then corrected for errors by filling sinks. Flow direction and accumulation were generated to properly account for the surface area contributing to the input of a given point along a stream. Finally, location points were used as "pour points" representing the most downstream point of each watershed and boundaries were delineated.

Coarse scale GIS data were used to generate land use input conditions. For this analysis we did not use the input node state definitions described by the working group because data supporting those classifications was not ready at time of publication. Instead, we kept the same state classifications, but defined them according to the available data. For example, rather than defining mining impacts based on Best Management Practice (BMP) usage (working group definition) we define mining impacts as the percentage of upstream watershed under mining permits.

Landscape-scale parameters were calculated based on publicly accessible data. Data used to calculate metrics include mining permit polygons and point locations of oil or gas wells acquired from the Kentucky Mine Mapping Information System (Commonwealth of Kentucky, 2003), digital land cover data from the 2001 National Land Cover Dataset (NLCD; 30 meter cell size) (U.S. Environmental Protection Agency, 2007), location of logging inspection sites from Kentucky Division of Forestry, and ArcGIS Streetmap data (ESRI, 2005). Calculated metrics include percent of watershed under mining permits, percent of watershed urbanized, percent of watershed pasture, number of logging inspection sites in watershed, well density, and road crossings over streams (Table 3). The percentage of watershed under mining permits was calculated by dividing the area permitted for mining in the watershed by the total watershed area. The percent of watershed urbanized was calculated by reclassifying 2001 NLCD raster data classified as low, medium, and high intensity developed (classes 22, 23, and 24) into "urban," calculating total urban area within each watershed, and dividing by the total watershed area. A similar method was used for percent of watershed as pasture, except we only used the pasture / hay NLCD class (81). Well density was used as a surrogate for unpaved roads because well locations are a major source of unpaved roads in this region. Well density was calculated as the number of wells per square kilometer of watershed. Lastly, road crossing density (over streams) was calculated as the number of road crossings per square kilometer of watershed.

Additionally, data for three biological inputs are required for model analysis: beaver presence and the size of populations within two distance categories. The presence \ absence of beavers for the watersheds used in this analysis was determined by visiting sites and surveying for signs of beaver activity. Immigration potential is a function of two nodes describing the relative size of populations within two distance categories: nearby (within radius of four stream miles) and distant (between four and ten stream miles). These distance categories were chosen because previous studies have observed individual blackside dace migrating up to four stream miles in a single year (Detar, 2004) and further hypotheses suggest that blackside dace can migrate up to ten stream miles over a life span.

Table 3. Land use condition metrics based on GIS analysis of direct upstream watersheds for two blackside dace populations.

Metric	Davis Branch	Big Lick Branch
Area of watershed	3.81 km^2	5.25 km^2
Percent of watershed mined	0	0%
Percent of watershed urbanized	1%	0%
Percent of watershed pasture	0%	0%
Density of wells	0	0%
Density of road crossings	0	0%
Number of logging sites	0	0
Beaver presence	Yes	No
Size of nearby populations	Low	Large
Size of distant populations	Low	Large

We calculated the size of blackside dace populations of the 52 populations from the original dataset within these stream distance categories by using ArcGIS Network Analyst (ESRI, 2005) to perform network based travel distances with our NHD stream layer. ArcGIS Network Analyst allows users to model network conditions to calculate metrics such as closest facility, travel directions, and service area (ESRI, 2005). However, we had to create a novel approach to correctly calculate stream miles because Network Analyst calculates distance only in a unidirectional manner (downstream distances are calculated, upstream distances are left as zero).

This novel approach can be applied with the following steps. We converted our NHD stream layer into a Network Dataset and created a new Closest Facility layer to determine the shortest stream path between two populations and calculate this distance (Figure 2). However, a two-step process was required to calculate the distance between two populations. First, one population was added as a Facility and the second was added as an Incident. Solving for this route provides the shortest stream path between two populations. However, upstream movements are calculated with a distance of zero, making the total distance incorrect. Therefore, we manually determined the first common downstream junction within the route. This junction is manually added as a Facility, while the first population is changed from Facility to Incident. Re-solving the network under this situation provides two routes to the same Facility. Adding the distances of the two routes is the correct distance between the two populations. A systematic progression of closest facilities was performed to determine the total population densities within four stream miles and four to ten miles. The total population densities within these radii constitute the conditions for the two immigration input nodes.

Query Tool

The data development described above required multiple ArcGIS data types, processes, and extensions. In order to simplify the linkage between ArcGIS and Netica, we developed a query tool within ArcGIS that displays the local condition data required to attribute the BBN. To minimize the requirement for managers to actually produce or manage data, we first created a geodatabase to store all data necessary for site description and BBN analysis. We then built a custom query tool using VBA scripting and ArcObjects in order to query the geodatabase for the spatial attributes and display this information in a well-organized manner.

Initially, each population is assigned a unique ID, which is attributed to the corresponding watershed and is used as a primary key, linking all geodatabase attribute tables. The query tool only works on a predefined layer of population points, preventing the users from selecting points without data. When points from the predefined layer are selected, a three-tabbed form containing the data is displayed. Each tab is thematic: one displays stream and site characteristics, one displays population characteristics, and one displays upstream land use conditions. This form is customizable to any type of data and can easily be altered if the BBN structure is altered or managers request additional information.

Case Studies

Using two case studies, we demonstrate how the BBN can be used to analyze current conditions and decisions that would cause changes to those conditions. The first stream population of interest is found in Davis Brach, in the Yellow Creek sub-basin. This population and direct upstream watershed are completely located within Cumberland Gap National Historic Park, affording it protection from the majority of land use inputs associated with human activity. However, beavers colonized the stream in 1993 and caused a major shift in stream habitat structure (Stephens, 2007). While this population represents an ideal example of protected populations favored by the blackside dace recovery plan objectives (U.S. Fish and Wildlife Service, 1988), it also represents an isolated population because of physical barriers (beaver dams, urbanization) and distance from other populations.

The second stream population is found in Big Lick Branch in the Cumberland River (below Cumberland Falls) sub-basin. This population and direct upstream watershed are managed by the Daniel Boone National Forest (DBNF), allowing for a much higher probability of human land use in the form of mineral extraction, road construction, and forest thinning (Daniel Boone National Forest, 2007) than the area containing the first stream population. Although the watershed surrounding Big Lick Branch has the potential to be used for natural resource extraction, local stream habitat conditions are currently pristine. While the qualities of the direct upstream watershed are currently similar to those of Davis Branch, land use decisions may eventually differ from those in Davis Branch. Additionally, this population interacts as part of a larger population mosaic, both providing emigrants and receiving immigrants (Detar, 2004).

Results and Discussion

Spatially-Explicit Analyses

The BBN was attributed with input node conditions for both Davis Branch and Big Lick Branch based on the previously described GIS data development (Table 3). All land use input nodes were attributed with the lowest impact state for both streams because human impacts in both watersheds are very low. However, the biological inputs are strikingly different, with Davis Branch having a very isolated population influenced by beavers, and Big Lick Branch having a beaver free stream that interacts with other populations.

Based on these inputs, the Davis Branch population is expected to have a 15.9% percent probability of becoming locally extirpated in five years, a 14.2% probability of declining, a 43.1% probability of remaining stable, and a 26.8% chance of growing. The results for the Big Lick Branch population are similar, with a 11.8% probability of becoming locally extirpated, a 10.3% probability of declining, a 45.1% probability of remaining stable, and a 32.8% probability of growing. The results from these analyses demonstrate that the population conditions at the two sites are relatively similar even though differences exist in model inputs. It should be noted that the conditions for Big Lick Branch represent the "best case scenario" for a population, with no land use inputs and high quality biological inputs. The group believed that the probability of extirpation under these pristine conditions seemed too high and therefore model refinement may take place. Now that responses have been predicted for each local population, we can also determine how decisions to change these conditions might affect the population.

Spatially-Explicit Decision Making

Managers may use the probability of population responses previously discussed to determine the relative health of a population both independently and in relation to other streams. However, in order to determine how different land use conditions would alter these probabilities, managers simply need to change the conditions of the input nodes. While this does not constitute a true decision support tool with a suite of input decisions influencing the land use inputs, it does allow managers to analyze possible land use changes. Future development of the model will incorporate an aforementioned suite of decisions influencing land use inputs.

Many biological and land use questions can be answered by altering the model inputs. For example, the effect of drought can be revealed by changing the monthly average streamflow to the "below normal" state. However, for this discussion we analyze two specific decisions for Davis Branch and Big Lick Branch.

The recent colonization of Davis Branch by beavers has caused some alarm to land managers because it may be negatively affecting blackside dace abundance (Stephens, 2007). Therefore, some managers have suggested removing beavers from this watershed in order to re-establish more typical blackside dace habitat. This scenario can be analyzed in the BBN simply by changing beaver presence in the Davis Branch model from "present" to "absent." When this change is made, population response remains relatively unchanged (Table 4). The lack of a strong response supports the belief that blackside dace can remain viable in this stream despite the presence of beavers. Therefore the National Park Service could use this as supporting information to prevent entering into a costly and protracted process of beaver removal.

According to the Daniel Boone National Forest website, "Seventy percent of the mineral resources (oil, gas and coal) underlying the surface of the [DBNF] is in private ownership" (Daniel Boone National Forest, 2007). Therefore it is plausible that DBNF would allow mining or drilling within the Big Lick Branch watershed. Biologists with the DBNF can alter land use input states to determine how these changes might affect the population response. Simply by changing the mining practices from "none" to "low impact," the predicted population response greatly changes (Table 5). The risk of local extirpation within the watershed more than triples and the cumulative probability of population growth and stability drop to less than 50%. This represents a major change in the population condition, and may compel managers to evaluate this decision very closely.

Conclusions

The BBN case studies discussed above (Davis Branch and Big Lick Branch) reveal the benefits for managing the blackside dace in a spatially-explicit framework. This modeling effort is spatially unique to specific populations while also being quantitatively consistent across populations because it is based on one comprehensive model of the blackside dace ecological system. Similarly, the data collected for each population are standardized. This allows managers to effectively compare the status of spatially divergent populations.

Table 4. Expected population response for Davis Branch based on current conditions and conditions following a beaver removal program.

Population response state	Using current conditions (%)	Using conditions following beaver removal (%)
Local extirpation	15.9%	12.3%
Population decline	14.2%	10.5%
Stable population	43.1%	44.8%
Population growth	26.8%	32.4%

Table 5. Expected population response for Big Lick Branch based on current conditions and conditions following low impact mining.

Population response state	Using current conditions (%)	Using conditions following low impact mining (%)
Local extirpation	11.8	36.3
Population decline	10.3	14.9
Stable population	45.1	30.5
Population growth	32.8	18.4

Furthermore, by altering the state(s) of the input node(s), managers can analyze the predicted changes in population response caused by changes in land use condition. Because this decision analysis is based on the expert judgment of an independent group of species experts, it can be used as support for or against land use changes. Quantifiable analysis of land use decisions can greatly assist land managers who receive pressure from many different stakeholders during the decision making process.

By organizing the collective ecological understanding of many species experts, our BBN provides agencies with a quantifiable, transparent, and consistent way to determine the relative health of any local population. We have simplified this process by organizing meaningful spatial data into one central geodatabase and developing a query tool to display specific spatial attributes and easily parameterize specific models. BBN modeling also gives managers a straightforward method to test possible changes in land use. The resulting changes in population response are easily understood and communicated, offering managers a way to share information with various stakeholders. By developing a universal model describing ecological linkages that is parameterized with spatially-explicit land use data, we may facilitate improved management of a threatened species.

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