STRUCTURED DECISION MAKING FOR RECOVERY MANAGEMENT OF A THREATENED SPECIES, *PHOXINUS CUMBERLANDENSIS* (BLACKSIDE DACE)

by

KEVIN TODD MCABEE

(Under the Direction of Nathan P. Nibbelink)

ABSTRACT

High uncertainty and few historic data hinder management of many imperiled species because recovery planning is often based heavily on expert opinion. While this is a practical place to begin, recovery planning must continually focus on incorporating the most up to date ecological knowledge. Decision analysis is one tool that can help managers quantitatively formalize the complex, uncertain and varying relationships found in most recovery management programs. I developed a model to support structured decision making for recovery management of the federally threatened blackside dace (*Phoxinus cumberlandensis*) by employing a Bayesian belief network (BBN). The completed model is an up to date description of the inputs and ecological variables believed by species experts to most impact recovery. Model analysis demonstrates variables that most influence management outcomes, which in turn can guide future research.

INDEX WORDS: Bayesian belief networks, blackside dace (*Phoxinus cumberlandensis*), endangered species, decision analysis

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DEDICATION

This thesis is dedicated to all of my friends and family that have spent time with me enjoying the beauty and wonder of the outdoors. My passion for conserving the natural resources of our planet owes a great deal to the wonderful memories I associate with being surrounded by nature and those I love.

I would like to thank my parents for giving me the love and support that allowed me to try anything that interested me. It is easy to try new things when you know you always have a safe place to return. I also thank them for taking me outside as much as possible as a child. Whether it was camping, fishing, or simply playing in the barn, the outdoors was always an inviting place.

Ultimately, I must give the greatest thanks to my wife Carly for sticking by me during the long winding path of my career. She has always been there to encourage me and lend a hand, no matter how crazy I have made our life.

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I must thank the Cumberlands HCP and the blackside dace working group members for giving me so much of their time and energy towards creating this project. Dr. Hayden Mattingly at Tennessee Tech University was receptive to my ideas and always willing to collaborate. The Cumberland HCP organizers (Alex Wyss and Trisha Johnson) provided lots of logistical support. Michael Floyd (USFWS) was always more than willing to chat and gave me the opportunity to actually hold a blackside dace. The National Park Service (Jim Long, Steve Bakaletz, Jenny Beeler and others) were interested in the model from the beginning and gave me the chance to explore the area by offering me housing. Others intimately involved in model creation include Tyler Black, Dave Pelren, Craig Walker, Ed Scott, Doug Stephens, Jim Williams, Matt Thomas and Brena Jones.

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TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

Many critics believe that the paucity of species de-listed from the Endangered Species Act (ESA) is a sign that the current system for imperiled species recovery is failing (Foin et al. 1998). To improve recovery of imperiled species, managers need to continually evaluate goals set forth in recovery plan documents by incorporating updates in ecological understanding and developing alternative management strategies. For such a process to be successful, managers must explicitly describe the knowledge on which decisions are based and communicate quantifiable decision outcomes. Decision analysis is a useful tool to support the recovery process because it provides users with a means to formalize relationships between variables, sources of uncertainty and management outcomes in quantitative models (Clemen 1996; Peterson & Evans 2003). For this reason, I developed a model for structured decision making with the intent of improving recovery management of the federally threatened minnow, *Phoxinus cumberlandensis* (blackside dace).

Two main objectives were accomplished in this thesis: 1) the creation of a comprehensive model describing the most up to date ecological knowledge about blackside dace; and 2) analysis of model outcomes to guide future management decisions and scientific research. Chapter Two presents a Bayesian belief network (BBN) model, documenting the current ecological knowledge in a graphical influence diagram that focuses on human and environmental stressors (inputs), ecological system components and management outcomes of interest. The model is then evaluated via sensitivity analysis, determining the relative influence of various inputs, actions, and variables on forecasted outcomes. Chapter Three evaluates specific alternative management actions using spatially explicit data from several watersheds inhabited by blackside dace. The process demonstrates the utility of BBNs for structured decision making, while also revealing how spatial information can be combined with Bayesian belief networks to facilitate the process.

To construct, refine and evaluate the decision model, I served as a "knowledge engineer," working closely with blackside dace experts and coalescing their collective beliefs into a single model (Nyberg et al. 2006). I developed this model within a Bayesian network following the guidelines in Marcot et al. (2006). Initially, I facilitated the construction of an influence diagram (or "ecological causal web") (Marcot et al. 2006) that graphically represents the most current understanding of blackside dace ecological structure. This influence diagram was then mathematically parameterized by species experts in the Bayesian network development software, Netica (Norsys 2007), creating an initial BBN. The model was tested and refined based on sensitivity analysis and agreement with expert opinion. Sensitivity analysis also was used to demonstrate the relative influence of variables on management outcomes. Using the completed model, various input scenarios were evaluated in order to describe the predicted blackside dace population response to assorted combinations of ecological stressors.

To explore spatially-explicit effects of various management actions, I used GIS and spatial data from 52 current blackside dace populations to parameterize models with site specific conditions. Two management actions in particular, beaver removal and low impact mining, were assessed because they represent actual blackside dace management questions provided by land managers. In addition to offering useful methods and tools for attributing spatially structured BBNs, this chapter demonstrates the utility of the BBN for evaluating real management options.

In total, this thesis presents a way to manage recovery of imperiled species via a structured decision making process using current, comprehensive ecological knowledge in a Bayesian belief network. This modeling framework improves the *current* management of blackside dace and will lead to a more effective *future* recovery management system.

Literature Review

Imperiled species recovery

Human activities are now recognized as the single greatest cause of decline in global biodiversity and alteration of species distribution patterns (Gaston 2005; Pimm et al. 1995; Sala et al. 2000). In the United States, the Endangered Species Act (ESA) is designed to combat this problem through a three step process of enlistment, protection and recovery (Foin et al. 1998). The enlistment and protection aspects of the ESA have accomplished the tasks of identifying imperiled species and providing these species legal protection from human harassment. However, very few species have actually recovered to sustainable population levels that would downgrade imperilment status or lead to complete removal of protection (Foin et al. 1998). Improving recovery management of imperiled species is the next step towards preserving biodiversity in the United States and beyond.

In this thesis, I define recovery management as any decision in the management process designed to enhance long term species persistence. Recovery management decisions, like most wildlife management regulatory decisions, are affected by many issues, including paucity of data, lack of funding for many programs, research and data spread across many people/agencies, political and social opposition to certain management programs and multiple sources of uncertainty. Specifically, imperiled species management is often based on substantially less historical data and more uncertainty because imperiled species are often highly specialized, narrowly dispersed, newly classified, or very sensitive (Flather & Sieg 2007). Additionally, management of imperiled species is burdened by the fact that incorrect decisions can lead to irrevocable consequences (species extinction).

These realities make it difficult for managers to create quantifiable recovery goals, such as those required under the ESA. It is difficult to choose an aspect of habitat, demographics or human impact on which to focus recovery goals (parameter selection) with little ecological knowledge of a species. Furthermore, even with good data and ecological knowledge, it is difficult to choose biological targets for individual survival or population persistence. Combine these scientific difficulties with the social implications of setting overly conservative recovery goals (potentially high economic cost) or overly liberal goals (potential species extinction) and the difficulty of imperiled species recovery management becomes truly evident.

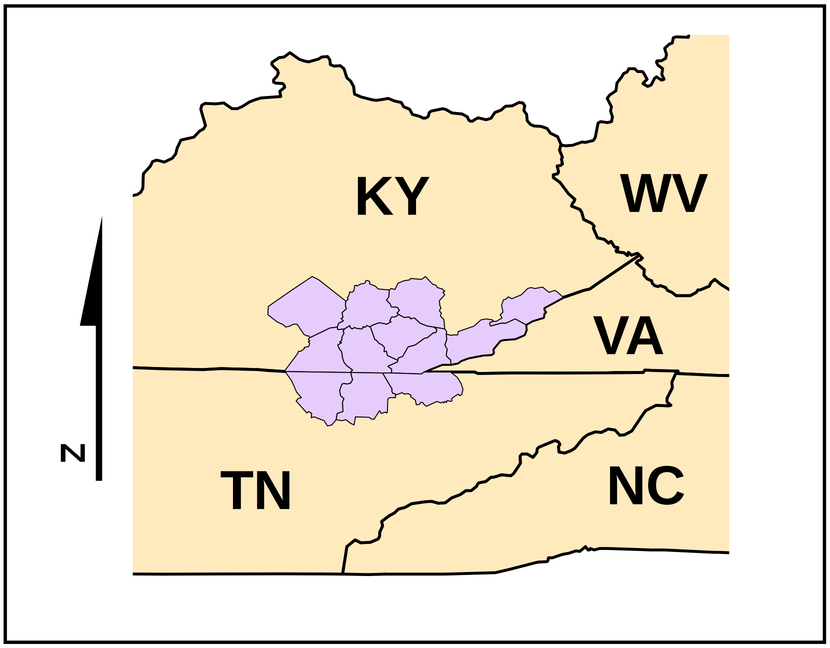
I address this difficulty by acknowledging that recovery plan goals are based on incomplete biological information and that recovery management decisions are greatly affected by uncertainty. Structured decision models can guide managers through complex issues by quantifying testable management outcomes. Additionally, these models are transparent to stakeholders and the community, facilitating peer review and scientific discussion. I propose that such a model can improve the recovery management of the blackside dace.

Blackside dace ecology

The blackside dace is a cyprinid species endemic to headwater streams in the Upper Cumberland River drainage of southeastern Kentucky and northeastern Tennessee, primarily in tributaries above Cumberland Falls, although a small number of populations occur below the falls (Etnier & Starnes 2001; Johnson et al. 2007; Starnes & Starnes 1978, 1981). Geographically, the species is only known to occur across eight counties in southeastern Kentucky and three counties in northeastern Tennessee (Johnson et al. 2007). Historical records indicate this species was likely first observed in the nineteenth century, but was regarded as a color variation of *Phoxinus erythrogaster* (southern redbelly dace) until 1978, when Starnes and Starnes officially recognized and described it as a unique species (Johnson et al. 2007; Starnes & Starnes 1978). At the time of its description in 1978, the species may have already been extirpated from much of its historic range, although its historic range is unknown (Starnes & Starnes 1978). Early hypotheses cited pervasive coal mining in the region as the primary cause for reduced distributions (Starnes & Starnes 1978, 1981).

Blackside dace habitat is usually characterized by clean, rocky substrate, cool, clear water and full riparian canopy (Black 2007; Detar 2004; Starnes & Starnes 1978, 1981). These streams are typically 2-5 meters wide, with a crude gradient between

Figure 1.1 Known distribution of blackside dace by county. Currently blackside dace are only known to occur in eight counties in Kentucky (Bell, Harlan, Knox, Laurel, Letcher, McCreary, Pulaski and Whitley) and three in Tennessee (Scott, Campbell and Claiborne).



1 and 6 percent and riffle:pool ratio less than 60:40 (Black 2007; Johnson et al. 2007; Jones 2005; Starnes & Starnes 1981). Streams with more than 60% riffle support fewer blackside dace populations and are more likely to be dominated by blacknose dace (*Rhinichthys atratulus*) and creek chubs (*Semotilus atromaculatus*) (Johnson et al. 2007). Habitat models demonstrate that blackside dace are more likely to occur in streams with turbidity less than 10 NTU, dissolved oxygen greater than 8.5 mg/L, summer water temperature less than 18.5 °C, and conductivity less than or equal to 240 µS (Black 2007; Johnson et al. 2007; Jones 2005).

Individual blackside dace have approximately a three year life span in the wild, grow to an average adult length of 50-65 mm and forage on diatoms, algal cells, root hairs, benthic macroinvertebrates and detritus (Black 2007; Etnier & Starnes 2001;

Starnes & Starnes 1978, 1981). Research has demonstrated that blackside dace are negatively correlated with the presence of the non-native redbreast sunfish (*Lepomis auritus*), a potential predator (Johnson et al. 2007; Jones 2005). Based on observational studies of reproductive behavior, blackside dace appear to be an obligate nest associate to creek chub and central stoneroller (*Campostoma anomalum*) (Cicerello & Laudermilk 1996; Mattingly & Black 2007; Starnes & Starnes 1981) and have been shown to hybridize with creek chubs (Eisenhour & Piller 1997). There is speculation that southern redbelly dace is a competitive invader, inhabiting streams with heavier silt loads and warmer water (Johnson et al. 2007; Starnes & Starnes 1978; US Fish and Wildlife Service 1988). Research has shown high co-occurrence between blackside dace and southern redbelly dace (Mattingly & Black 2007), but no empirical data demonstrate that southern redbelly dace displace blackside dace.

Blackside dace conservation

In response to limited distribution, continuing local extirpation events after 1978 (O'Bara 1985) and threats to habitat conditions from forestry and mining activities, the blackside dace was listed by the United State Fish and Wildlife Service (USFWS) as federally threatened in 1987 (US Fish and Wildlife Service 1987). Within a year, the USFWS had also published a recovery plan for the species, with the primary purpose of "[restoring] viable populations of the blackside dace to a significant portion of its historic range" (US Fish and Wildlife Service 1988). Criteria for successful recovery include: 1) the establishment of three viable populations in each of eight sub-basins; 2) habitat protection (public ownership or conservation easements) for all of these populations; 3) the absence of future threats; and 4) improved coal activities and substrate quality throughout the species range, and subsequent blackside dace colonization of previously uninhabited stream reaches (US Fish and Wildlife Service 1988).

Because the blackside dace was not officially described until 1978, the ecological knowledge used to set recovery goals in 1988 was sparse and general in nature. While the objectives were likely justified given the state of knowledge at the time, the recovery plan sets both quantitative (number of populations) and qualitative objectives that are based on untested assumptions. Therefore, uncertainty surrounds many aspects of the recovery plan. For example, the establishment of three protected, inhabited stream reaches in each of eight sub-basins (criteria 1) (US Fish and Wildlife Service 1988) may not assure range-wide persistence of the species. Additionally, protection of populations through land ownership (criteria 2) may either be too strict (prohibiting land use) or too conservative (not protecting the entire upland watershed habitat). Since 1988, many more surveys and ecological studies have been conducted on blackside dace. The recovery plan would be well served to incorporate this knowledge into an updated set of recovery objectives.

Updates in blackside dace ecological understanding

Since publication of the blackside dace recovery plan in 1988, a number of sampling surveys and ecological research projects have supported initial observations by Starnes & Starnes (1978, 1981) while also elucidating new information about blackside dace ecology. The known distribution of blackside dace has increased from 35 streams in 1988 (US Fish and Wildlife Service 1988) to approximately 105 streams in 2008 (personal communication with Michael Floyd, U.S. Fish and Wildlife Service), demonstrating the species is more widespread than originally believed. Observations of spawning behavior indicate that blackside dace depend heavily on nests developed by other species, such as *Semotilus atromaculatus* (creek chub) (Cicerello & Laudermilk 1996; Mattingly & Black 2007). Research has also shown that spawning activities are affected by substrate embeddedness levels related to logging activity, indicating that land use practices other than coal mining should be considered for recovery criteria (Mattingly & Black 2007). Movement studies show blackside dace have complex movement patterns and can move as far as four kilometers in one year (Detar 2004), highlighting the need to maintain quality habitat corridors between populations. Habitat models have revealed key ecological conditions for the species (Black 2007; Jones 2005), providing a means to estimate the effect of potential changes to the stream and associated upland habitat. These studies have greatly improved the understanding of life history requirements of blackside dace.

While recovery managers may be using some of the new information when making recovery decisions, the data has not been formally incorporated into the recovery plan criteria. Additionally, if managers are using this data when making decisions, they are most likely using their best judgment guided by experience and existing knowledge of the ecological system; hence, the anticipated outcomes of management actions are not quantified. In this thesis, I demonstrate how a Bayesian belief network modeling approach can formally house a quantitative model for blackside dace persistence by combining expert judgment with empirical data. The model can be used to effectively communicate ecological relationships to recovery managers and other stakeholders.

Further, I demonstrate how the model predicts consequences of management actions on blackside dace populations based on current knowledge, but more importantly provides a means to test these predictions against actual outcomes. Cumulatively, the model supports current decision making, while also supporting modifications in future management actions as continued refinement in ecological understanding occurs.

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CHAPTER 2

ESTABLISHING A STRUCTURED DECISION MAKING PROGRAM FOR A FEDERALLY THREATENED MINNOW, BLACKSIDE DACE[1]

[1] McAbee, K., and N. Nibbelink. To be submitted to Biological Conservation

Introduction

In the United States, the Endangered Species Act (ESA) is designed to protect imperiled species through a three step process of enlistment, protection and recovery (Foin et al. 1998). The enlistment and protection aspects of the ESA have accomplished the tasks of identifying imperiled species and providing these species legal protection from human harassment. However, very few species have actually recovered to sustainable population levels leading to either a downgrade in imperilment status or complete removal of protection (Foin et al. 1998). Disturbingly, in the first 28 years of the ESA, only six species had recovered to population levels that permitted delisting, while 1243 species were still listed as threatened or endangered (Hoekstra et al. 2002). Although many critics believe that the paucity of species de-listed from the ESA is a sign that the current system for imperiled species recovery is failing (Foin et al. 1998), proponents believe that the process has and will continue to improve in both planning and implementation (Crouse et al. 2002; Hoekstra et al. 2002).

A fundamental requirement for continued improvement is the inclusion of dynamic, explicit science in recovery plans (Boersma et al. 2001) because these plans guide management decisions. However, even after incorporating explicit science, recovery decisions for imperiled species must contend with four primary sources of difficulty in decision making: ecological complexity; multiple sources of uncertainty; multiple, possibly competing objectives; and differing stakeholder values (Clemen 1996). Decision analysis is one tool that can help decision makers quantitatively formalize complex, uncertain, and varying relationships, thus making better decisions through the careful consideration of available information and deliberation of possible outcomes

(Clemen 1996; Peterson & Evans 2003). Through the use of decision analysis models, managers can examine the influence of ecological variables and management alternatives, incorporate multiple sources of data (such as empirical models and expert judgment), acknowledge uncertainty, and make quantitative predictions of outcomes (Clemen 1996; Peterson & Evans 2003).

Formalizing the ecological complexities and quantifying decisions is especially important for imperiled species recovery because certain qualities of imperiled species produce unique management difficulties (Marcot & Molina 2007). Often, imperiled species are highly specialized, narrowly dispersed, newly classified or very sensitive, making them difficult to detect and often precluding experimentation (Flather & Sieg 2007). These obstacles frequently lead to minimal existing data and high uncertainty (Marcot & Molina 2007). As a result, when initially creating recovery plans, managers must rely on their expert judgment and establish means objectives they believe promote species persistence. However, these judgments can sometimes erroneously become ingrained as fact rather than belief. Therefore, as more information is collected, it is imperative to re-evaluate recovery objectives. To this end, recovery management should take a structured decision making approach.

In this manuscript I present a model used for structured decision making to support threatened and endangered species recovery management by employing a quantitative framework in the form of a Bayesian belief network (BBN). Specifically, the model presented here is a description of land use and environmental conditions (inputs) and ecological variables believed to most influence recovery of the federally threatened blackside dace (*Phoxinus cumberlandensis*). A team of scientists and managers worked together to develop this decision model, demonstrating the opportunity for scientific collaboration and interdisciplinary research in decision analysis (Peterson & Evans 2003). Most importantly, the analysis of the completed model offers guidance for decision making in the form of testable, transferable and transparent results.

This study had two primary objectives: 1) collaboratively develop a usable decision model incorporating the best empirical data and expert knowledge and 2) evaluate the model and its utility for decision making through sensitivity analysis and scenario building. Initially, a Bayesian belief network describing the blackside dace ecological system was developed, documenting the current understanding of system structure. Sensitivity analysis assessed the relative influence of inputs and variables on management outcomes. Finally, several land management scenarios were constructed to evaluate predicted blackside dace population response to various combinations of ecological stressors. Overall, this process demonstrates the benefits of decision analysis for managing recovery of imperiled species.

Blackside dace (*Phoxinus cumberlandensis*)

The blackside dace is a cyprinid species endemic to tributary streams in the Upper Cumberland River drainage of southeastern Kentucky and northeastern Tennessee (Etnier & Starnes 2001; Starnes & Starnes 1978, 1981). Historical records indicate this species was likely first observed in the nineteenth century, but was regarded as a color variation of *Phoxinus erythrogaster* (southern redbelly dace) until 1978, when Starnes and Starnes officially recognized and described it as a unique species (Johnson et al. 2007; Starnes & Starnes 1978). At the time of its official description in 1978, the species may have already been extirpated from much of its historic range, although its historic range is unknown (Starnes & Starnes 1978).

Blackside dace habitat is usually characterized by clean, rocky substrate, cool, clear water and full riparian canopy (Black 2007; Detar 2004; Starnes & Starnes 1978, 1981). These streams are typically 2-5 meters wide, with a crude gradient between 1 and 6 percent and riffle:pool ratio less than 60:40 (Black 2007; Johnson et al. 2007; Jones 2005; Starnes & Starnes 1981). Habitat models demonstrate that blackside dace are more likely to occur in streams with turbidity less than 10 NTU, dissolved oxygen greater than 8.5 mg/L, summer water temperature less than 18.5 °C, and conductivity less than or equal to 240 μS (Black 2007; Johnson et al. 2007; Jones 2005).

Individual blackside dace have approximately a three year life span in the wild, grow to an average adult length of 50-65 mm and forage on diatoms, algal cells, root hairs, benthic macroinvertebrates and detritus (Black 2007; Etnier & Starnes 2001; Starnes & Starnes 1978, 1981). Based on observational studies of reproductive behavior, blackside dace appear to be an obligate nest associate to creek chub (*Semotilus atromaculatus*) and central stoneroller (*Campostoma anomalum*) (Cicerello & Laudermilk 1996; Mattingly & Black 2007; Starnes & Starnes 1981) and have been shown to hybridize with creek chubs (Eisenhour & Piller 1997). Movement studies show blackside dace have complex movement patterns and can move as far as four kilometers in one year (Detar 2004), highlighting the need to maintain quality habitat corridors between populations.

Because of its limited distribution, continuing local extirpation events (O'Bara 1985) and threats to habitat conditions from forestry and mining activities, the blackside dace was listed by the US Fish and Wildlife Service (USFWS) as federally threatened in 1987 (US Fish and Wildlife Service 1987). Criteria for successful recovery included: 1) the establishment of three viable populations in each of eight sub-basins; 2) habitat protection (public ownership or conservation easements) for all of these populations; 3) the absence of future threats; and 4) improved coal activities and substrate quality throughout the species range, with subsequent blackside dace colonization of previously uninhabited stream reaches (US Fish and Wildlife Service 1988).

Since 1988, the known distribution of blackside dace inhabited streams has increased from 35 (US Fish and Wildlife Service 1988) to approximately 105 in 2008 (personal communication with Michael Floyd, U.S. Fish and Wildlife Service), demonstrating the species is more widespread than originally believed. Research has also shown that spawning activities are affected by substrate embeddedness levels related to logging activity, indicating that land use practices other than coal mining should be considered in the recovery criteria (Mattingly & Black 2007). Habitat models have revealed key ecological correlates for the species (Black 2007; Jones 2005), providing a means to evaluate potential changes to the stream and associated upland habitat. These and other studies have greatly improved the understanding of the life history requirements of blackside dace. I will now describe how a group of species experts collaborated to create a model that incorporated new ecological knowledge into a comprehensive decision analysis model for this species.

Methods

I followed the three fundamental steps of structured decision modeling described by Clemen (1996). An essential first step to a decision analysis model is to identify and structure values and objectives (Clemen 1996; Peterson & Evans 2003). Objectives should be separated into fundamental and means objectives, indicating which objectives are the true goals of the project (fundamental) and which objectives simply help achieve other objectives (means) (Clemen 1996). For this project, the fundamental objective is the persistence of blackside dace populations at currently monitored sites, while the means objectives are maintaining quality habitat and promoting natural life history traits.

The second step of structured decision making is creating a logical framework in which to model the decision (Clemen 1996). I chose to structure the blackside dace decision model in a specialized influence diagram, a Bayesian belief network (BBN). Bayesian belief networks are directed acyclic graphs used to represent the relationship between variables in a probabilistic manner (Pollino et al. 2007). BBNs are increasingly being used for natural resources problems, such as: water planning (Cain 2001), land management (Rieman et al. 2001), ornithology (Martin et al. 2005), habitat assessment (McNay et al. 2006; Smith et al. 2007), population viability (Marcot et al. 2001; Steventon et al. 2006) and decision analysis (Conroy et al. 2008; Marcot et al. 2006a; Pollino et al. 2007). In wildlife management, BBNs are used to describe the cascade of influences that shape management outcomes of interest (Marcot et al. 2006b). In order to incorporate the most comprehensive and current ecological knowledge, a working group of blackside dace experts (Appendix C) was assembled to assist in construction of this Bayesian belief network.

Involving experts offered many benefits to the modeling process, including: incorporating as much knowledge as possible; tailoring the model to end users; and promoting a sense of teamwork within the management process. I invited numerous scientists from a variety of backgrounds to participate in the modeling process. This diverse group of scientists represented federal and state agencies, research universities and non-profit organizations and provided similarly diverse skills, knowledge, and experience. For logistic and structural support, I partnered with the Cumberlands Habitat Conservation Plans (HCP), a scientifically-based conservation partnership (Cumberlands HCP 2008). The Cumberlands HCP functioned as a valuable central agent in the creation of the model because the HCP's goals strongly parallel those of this project (Cumberlands HCP 2008).

The final step of structured decision making is defining and refining the elements of the decision (Clemen 1996). Elements within the blackside dace model were first defined using scientific support and empirical data, with the goal of including dynamic, explicit science within the plan (Boersma et al. 2001). Where empirical data was not available, elements were defined using the expert judgment of working group members. Model refinement was performed throughout the model development process. Additionally, model analysis presented in this manuscript offers guidance for future model refinement.

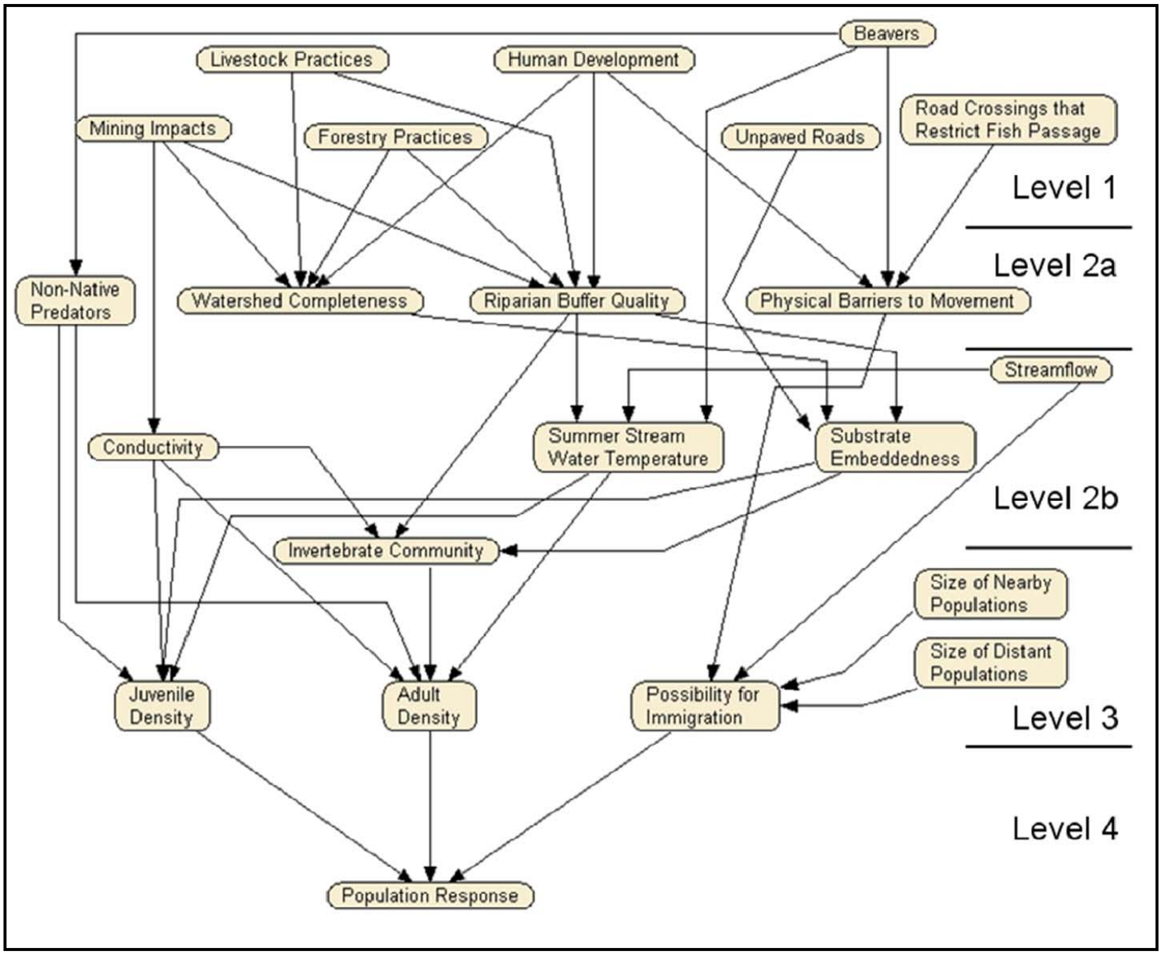
Development of an initial BBN

Following Marcot et al. (2006b), the first step of BBN development is the creation of an influence diagram representing ecological linkages that affect the species of interest. To elicit these linkages, I first performed a literature review, establishing a strong scientific foundation for the model. Early blackside dace researchers investigated life history and taxonomic information (Cicerello & Laudermilk 1996; Eisenhour & Piller 1997; Starnes & Starnes 1978, 1981) and conducted surveys of population locations (O'Bara 1985), while recent researchers have created and tested habitat models (Black 2007; Jones 2005), calculated population estimates (Black 2007; Detar 2004; Stephens 2007) and examined ecological relationships (Mattingly & Black 2007; Mattingly & Contributors 2005). I also worked with the Cumberlands HCP Science Advisory Committee, reviewing a summarized species account and expert opinions they had collected for species assessment (Johnson et al. 2007).

As part of the HCP development, blackside dace experts completed an exhaustive survey, eliciting opinions and recommendations concerning coarse threats (land use), fine threats (habitat and biological effects), linkages between threats and outcomes, life history and the uncertainty surrounding ecological knowledge (Johnson et al. 2007). Originally the surveys were designed to inform the Cumberlands HCP about land uses likely to cause current and/or future negative impacts to blackside dace (Johnson et al. 2007), but responses also provided BBN facilitators with a general scientific review for the construction of a rough draft influence diagram.

In December of 2007, a draft influence diagram was presented to the working group of blackside dace experts, which was discussed and modified until consensus was obtained (Figure 2.1). The updated influence diagram was developed and ratified through an open discussion that included the exchange of knowledge (data, conditions and trends), respectful debate of ecological hypotheses and dialogue concerning future

Figure 2.1. Influence diagram demonstrating the cascade of ecological influences upon blackside dace population response. Overall structure demonstrates that human and environmental inputs (Level 1) influence ecological variables (Level 2a and 2b) and life history (Level 3) that shape local blackside dace population response (Level 4).



application of the model. Therefore, the resulting ecological causal web was supported by the group as a whole, but may not represent the exact views of any one individual.

Modifications to the diagram were made by removing non-essential variables, thus simplifying the model. For example, members chose to remove any measure of human sewage inputs into streams because although they felt this was a major problem locally, over the entire range of the species they believed it was minor problem. Members also chose to include only one variable of water quality, conductivity. Stream pH was removed because it was not shown to be significantly associated with blackside dace presence in recent habitat modeling efforts (Jones 2005). The concentrations of metals associated with mine drainage were not included because the expenses associated with testing for these metals were believed to be too great for consistent monitoring. Ecologically, measures of competition (density of southern redbelly dace) were eliminated because there was little empirical support defining this relationship.

When finalized, the group structured the influence diagram with four levels of variables representing: 1) human and environmental inputs; 2) key ecological correlates of 2a) associated upland habitat conditions and 2b) stream habitat conditions; 3) biological (life history) effects; and 4) population response (Figure 2.1). The draft influence diagram contained a set of variables and the linkages between them, but in order to turn this diagram into a BBN, each variable was divided into a set of discrete states (Cain 2001; Marcot et al. 2006b; Pollino et al. 2007). To accomplish this task, each member was asked to suggest a method with which to measure each variable (with units) and define ecologically meaningful discrete states within the range of measurements. Members were asked to provide documentation to support their choices. Responses were analyzed by the facilitators and applied to each variable, providing units and mutually exclusive states. After slight modifications by the working group, the mutually exclusive states (Figure 2.2) and the units upon which they were defined (Appendix A) were ratified in February of 2008.

Using these unique states for each variable, initial BBN structure was parameterized with conditional probabilities. To parameterize conditional probabilities for variables within the model, individual member responses were averaged, which was the best compromise because all opinions were given equal weight. The conditional probabilities were then accepted by all members, which resulted in the alpha model (Marcot et al. 2006b) of the blackside dace BBN.

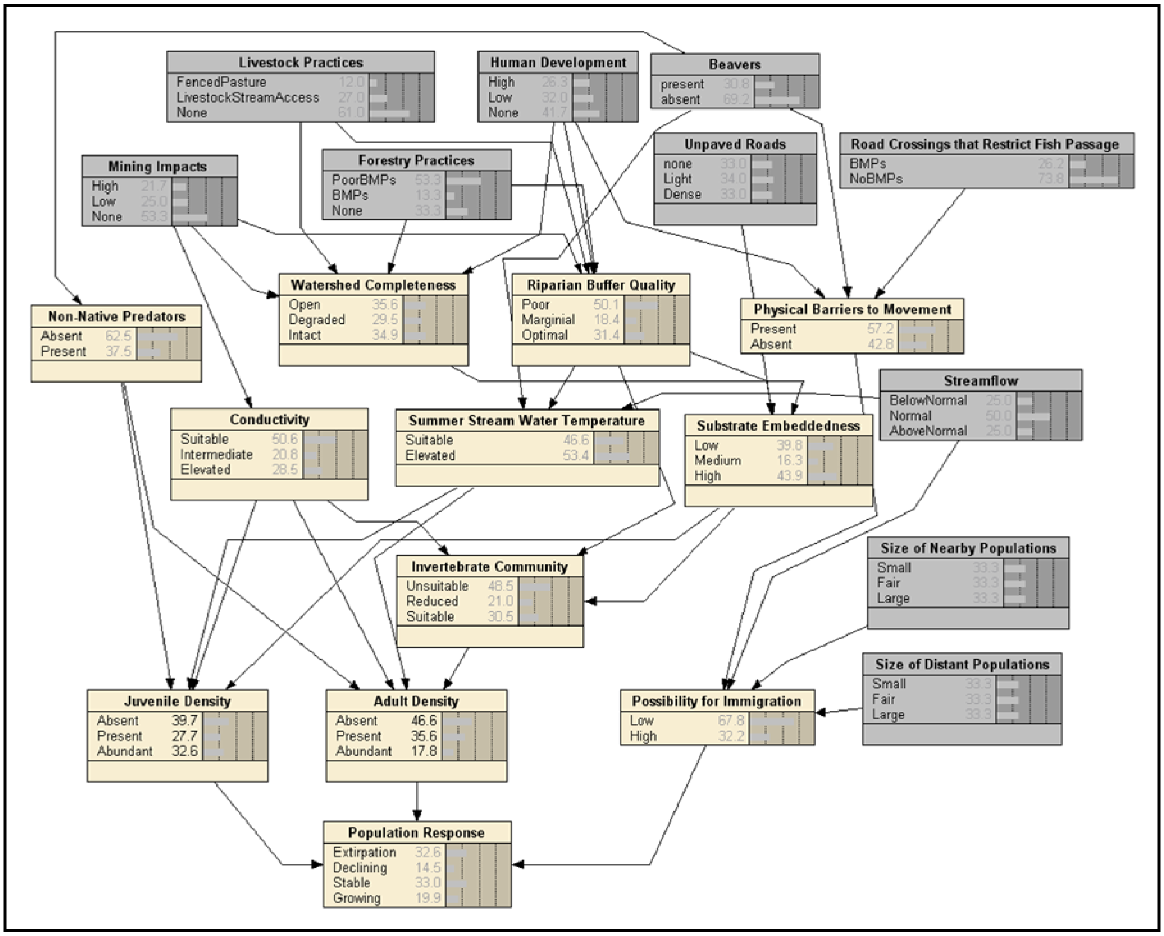
Completed model structure

The completed model represents how current conditions will influence blackside dace populations over a five year period. Ecological conditions (including a population estimate) are measured at year zero, while the management outcome is predicted for year five. The working group decided to measure population response on a five year time step because the life span of the blackside dace is estimated to be three to four years (Johnson et al. 2007; US Fish and Wildlife Service 1988). By using a time period slightly longer than the life span, users can assume local extirpation if no reproduction or colonization occurs.

The spatial extent of the model is 200 meter stream reaches known to harbor blackside dace populations. This extent was chosen to duplicate the population density and habitat modeling protocols described in Detar (2004), Jones (2005) and Black (2007). Data supporting model variables describing fish densities and stream habitat conditions are therefore collected in this 200 meter stream reach. However, human inputs and associated upland habitat variables are based on conditions in the entire upstream watershed from these sites. In general, only one 200 meter reach should be established within a 12-digit Hydrologic Unit Boundary (HUB) (US Geological Survey 2007).

The fundamental objective of the working group was to preserve blackside dace populations at currently inhabited streams. Therefore, the model outcome was designed

Figure 2.2. Division of influence diagram variables into mutually exclusive states, constituting the initial BBN structure. Dark grey boxes are parentless inputs.



to predict population trends at currently monitored sites. The population response was represented by four states: local extirpation; population decline; stable population; and population growth (Figure 2.2). Population growth and decline were defined as a population change greater than 10% in the positive and negative direction respectively. A stable population was defined as a population that remains within those bounds. Management outcomes are broken into states that represent absolute failure (extirpation), biological take (population decline), and success (stable and growing populations). These outcomes may be interpreted differently based on the state of the initial population, but they nonetheless provide a way to generally characterize population response to inputs.

The means objectives of the project included maintaining quality habitat for the species. Stream habitat conditions have been the most heavily investigated aspect of blackside dace ecology and therefore are the key proximal influences within the BBN (Figure 2.1, Level 2b). Two habitat modeling studies demonstrated that blackside dace presence/absence is strongly associated with conductivity and mildly associated with summer stream temperature (Black 2007; Jones 2005). Additionally, blackside dace reproductive activity is negatively related to substrate embeddedness (Mattingly & Black 2007). Therefore, these three parameters are central to the model. Each of these variables is also divided into unique states based on the results of associated studies (Appendix A). For example, models show that blackside dace are much more likely to inhabit streams with conductivity below 240µS (Black 2007; Jones 2005). The working group also chose to include a measure of invertebrate community health to represent blackside dace forage base and to act as a surrogate for other water quality parameters (Barbour et al. 1999).

Land use inputs, representing the top level of the network (Figure 2.1, Level 1), are those conditions most likely to occur in the region and subsequently affect the ecology of the blackside dace, specifically the three local habitat variables described above. Based on information provided in the Cumberlands HCP blackside dace species account document, mining and forestry practices are believed to pose the greatest threat to the persistence of the species (Johnson et al. 2007). Secondary threats found throughout the species range include human development (urbanization, construction, etc), poor livestock practices, road crossings that restrict fish movement and sedimentation from unpaved roads (Johnson et al. 2007). The presence of beavers was selected as an input because beavers alter stream conditions in ways believed to degrade blackside dace habitat (Stephens 2007). Streamflow was selected as an environmental input because water levels and flow regime are a key aspect of fish habitat (Freeman & Marcinek 2006).

The first level of ecological variables (Figure 2.1, Level 2a) contains upland habitat variables linking land use inputs to stream habitat conditions and biological effects. For example, forestry practices can increase substrate embeddedness through sedimentation inputs, but riparian buffers can mitigate this relationship (Barbour et al. 1999). The watershed completeness variable represents percent forest cover in the watershed outside the riparian zone. Two additional variables, non-native predators and physical barriers to movement, are included as binary states of present or absent.

Human and environmental inputs and associated upland conditions influence the stream habitat conditions described above (conductivity, stream temperature, substrate embeddedness, and invertebrate community; Figure 2.1, Level 2b). These variables subsequently influence blackside dace individuals at different stages of life history. Therefore, three biological effects describe the success of juveniles, adults and immigrants (Figure 2.1, Level 3). The three population parameters, representing the second means objective of the project (promoting natural life history characteristics), shape the management outcome of interest, blackside dace population response (Figure 2.1, Level 4).

Sensitivity analysis

As part of model refinement, sensitivity analysis was performed within Netica (Norsys 2007) for the completed blackside dace model to determine variables having the greatest influence on the outcome of interest (Rieman et al. 2001). BBN sensitivity analysis determines the relative influence of an individual variable by varying it across all possible states, while keeping all other variables constant (Rieman et al. 2001). Resulting variation in the outcome probability can therefore be attributed to changes in the variable being tested. Specifically, I calculated the relative influence of network components on the population response outcome. Although the outcome contains four states, for ease of communication I review only the sensitivity of the *local extirpation* state because preventing local extirpation is a fundamental objective of the project. As part of structured decision making, sensitivity analysis provides decision makers with a means to determine what factors are most influential to the decision outcome and are a useful way to refine the model (Clemen 1996).

Before the model was ratified, sensitivity analysis was presented to the working group as a step for model verification. Used as model verification, sensitivity analysis verifies that model structure matches expert expectations on the relative influence of variables (Marcot et al. 2006b). Deviations from expectations may require model refinement or reveal model features that require additional research.

Scenario building

Another type of sensitivity analysis can be performed by making changes in one or more aspects of the model, thus testing “what if” scenarios (Clemen 1996). After this type of analysis, the decision maker may want to re-evaluate the model or may want to more carefully consider variables of importance when making decisions. In this scenario analysis, I focused on creating combinations of inputs that represent real world management conditions for the blackside dace by setting input variables to specific states, but allowing intermediate variable states to vary based on probability tables. Input variables set to known states for scenario building were mining impacts, livestock practices, forestry practices, human development, unpaved roads, beavers, road crossings that restrict fish passage, streamflow, and size of nearby and distant populations.

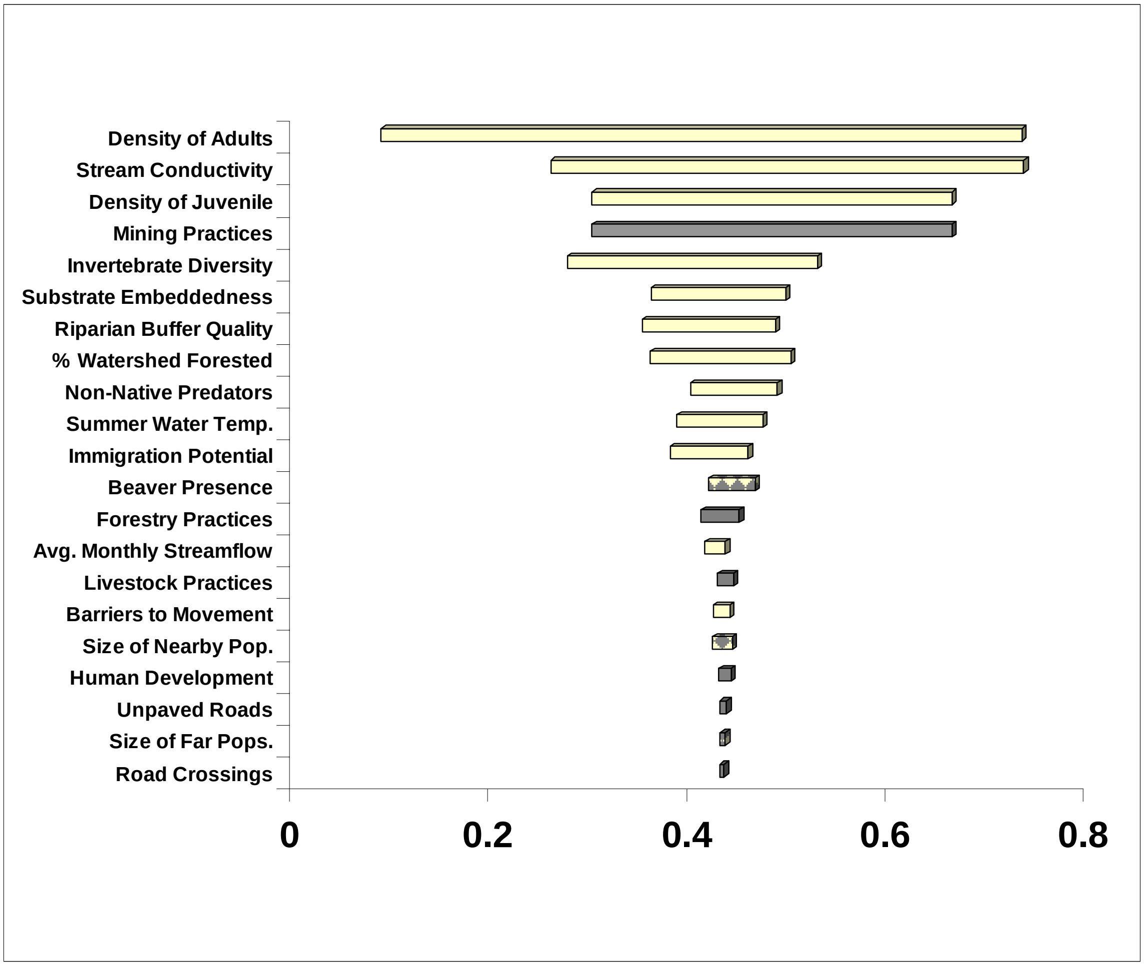
Four scenarios were developed to explore affects of alternative input conditions on model outcomes: 1) the most optimal input states (described below); 2) single environmental stressors (drought and beaver presence); 3) land use change caused by humans (logging and mining); and 4) multiple stressors. The most optimal input states (scenario 1) includes all human land use variables (mining, logging, livestock, human development, and unpaved roads) being set to 'none' and the road crossing variable being set to 'BMPs'. Optimal input states also include environmental inputs being set to represent beaver absence, strong metapopulation interaction (large blackside dace populations both nearby and distant), and above normal stream flow. Single environmental stressors (scenario 2) were tested by changing the state of a single input variable to a less optimal state, but maintaining all other inputs at the optimal state. Doing so demonstrates how the associated concept influences blackside dace population response when all other conditions are optimal. For example, changing the streamflow state to 'below normal' represents drought conditions. Human land use can be analyzed by changing the BBN in a similar manner (scenario 3). For example, when all other inputs are optimal and the forestry practices node is set to 'BMPs', the model represents a pristine watershed being logged using the BMPs most important for protecting blackside dace (Floyd & Stringer 2005).

While these scenarios demonstrate the effect of a single change under optimal conditions, the reality is that optimal conditions are uncommon and land use within a watershed is often more varied than one single practice. Therefore, it is useful to understand how multiple stressors work together to influence the predicted response of blackside dace populations (scenario 4). These stressors could both be environmental (drought and beaver), human derived (logging and livestock), or a combination (logging and drought).

Results

Sensitivity analysis (Figure 2.3) demonstrated that the probability of local extirpation was most strongly influenced by the density of adults. Figure 2.3 also demonstrates the probability of local extirpation was most strongly influenced by stream conductivity in the stream habitat condition level (Level 2b) and mining practices in the human land use level (Level 1). Varying stream conductivity across the three possible states causes the probability of local extirpation to vary between 26 and 74%, demonstrating that changes in stream conductivity can greatly alter the predicted blackside dace population response. These results are consistent with recent habitat modeling efforts conducted by students at Tennessee Tech University, which demonstrate that the "best performing [blackside dace] habitat models all [include] water conductivity as a predictor variable" (Black 2007; Jones 2005). Although the most influential node is

Figure 2.3. Sensitivity of the mean probability of local extirpation state at the population response node. The probability of local extirpation is most influenced by adult density, stream conductivity in the stream habitat condition level (Level 2b) and mining practices in the input level (Level 1). The bars show the change in local extirpation probability when the associated node (y-axis) is changed across their possible states, while all other nodes remain constant. Human land use inputs are darkened and biological inputs are checkered.



density of adults, this is largely a result of the direct linkage between the adult density node and the population response node. This result does have management applicability, demonstrating that adult density is a strong indicator of the future population response.

Scenario building

Scenario 1: *Blackside dace response to optimal conditions*

Under optimal conditions (defined above), a blackside dace population sampled in a 200 meter reach within a 12-digit HUB is predicted to have a 10.3% probability of local extirpation and 9.3% probability of a declining after five years. Additionally, the population is predicted to have a 45.7 and 34.7% probability of remaining stable or growing, respectively (Table 2.1). This indicates that the working group believes that under optimal habitat conditions, blackside dace populations have a less than 20% probability of being negatively impacted (sum of extirpation and declining states). The group agreed that a 10% probability of local extirpation in five years is somewhat high, but chose to not to make changes to the current model parameterization because they believed the model represented the current state of knowledge.

Scenario 2: *Blackside dace response single environmental stressors (drought and beaver)*

The presence of drought increases local extirpation (12.6%) and declining population (10.9%) probabilities only slightly from the optimal scenario, indicating that blackside dace populations should be robust to drought conditions over monthly time periods when other inputs are optimal (Table 2.1). Similarly, the presence of beavers only slightly raises the probability of local extirpation (13.9%) and population decline (13.1%) from optimal conditions (Table 2.1). While this seems to disagree with the experts' hypotheses concerning beaver, it highlights a limitation of the model. Most experts agree that within five years, this prediction is probably accurate because beaver produce a

Table 2.1. Predicted population response under optimal conditions and when changing the state of a single node. Under optimal conditions, blackside dace have a relatively low probability of negative population trends. While other disturbances (e.g. drought, beaver, logging) increased the probability of local extirpation slightly, mining showed the greatest potential for population effects, tripling the probability of extirpation, even for low impact mining.

* Unless described, all other input nodes are set to levels optimal for blackside dace.

Inputs *	**Predicted population response (% probability of being in each state)**			
	Local extirpation	**Population decline**	**Stable population**	**Population growth**
Optimal	10.3	9.31	45.7	34.7
Drought (below normal streamflow)	12.6	10.9	44.9	31.6
Beaver present	13.9	13.1	44.4	28.6
Logging with BMPs	11.5	10.3	45.1	33.1
Low impact coal mining	33.8	14.9	31.7	19.6
High impact coal mining	51.6	16.2	21.2	11.1

legacy effect and may not greatly change habitat until ten or fifteen years after colonization. Additional models including extended temporal predictions may be needed to represent this reality.

Scenario 3: *Blackside dace response to changing land use*

The predicted blackside dace population response to a logging operation using BMPs was only slightly more negative (11.5% extirpation and 10.3% decline probabilities) than optimal conditions (Table 2.1). Contrastingly, mining in the watershed greatly affected blackside dace population response. When the mining practices node was set to ‘low’, local extirpation had the highest associated probability (33.8%) of any population response state (Table 2.1). Moreover, with mining being set to ‘high impact’, the probability of local extirpation (51.6%) was higher than all other

Table 2.2. Predicted population response under multiple stressors. Highly negative population responses are not predicted for combinations of less influential inputs.

* Unless described, all other input nodes are set to levels optimal for blackside dace.

Stressors *	**Predicted population response (% probability of being in each state)**			
	Local extirpation	**Population decline**	**Stable population**	**Population growth**
Drought and beaver presence	16.3	14.4	42.9	26.4
Drought and logging without BMPs	17.8	14.4	41.7	26.1
Logging without BMPs and livestock accessing the stream	16.3	13.7	42.6	27.4

Table 2.3. Predicted population response under multiple stressors that include mining. Highly negative population response trends are predicted when less influential inputs occur in combination with mining.

* Unless described, all other input nodes are set to levels optimal for blackside dace.

Inputs *		**Predicted population response (% probability of being in each state)**			
Initial stressor	**Mining level**	**Local extirpation**	**Population decline**	**Stable population**	**Population growth**
Drought	Low impact	37.9	14.8	29.6	17.6
	High impact	57.1	14.9	18.6	9.4
Logging with BMPs	Low impact	34.5	15.1	31.3	19.0
	High impact	52.7	16.2	20.6	10.5
Beavers present	Low impact	38.6	15.9	29.0	16.4
	High impact	56.9	15.8	18.2	9.1

population response states combined (Table 2.1). These results follow the expectations of the group (and the sensitivity analysis), indicating that of all the input nodes, mining has the greatest potential to influence blackside dace population response.

Table 2.4. Comparison of mining influence to the cumulative influence of all other input nodes. The probability of negative population responses are more likely when mining occurs alone than when all other stressors act cumulatively.

Inputs		Predicted population response (% probability of being in each state)			
Mining	**Other input nodes**	**Local extirpation**	**Population decline**	**Stable population**	**Population growth**
None	Least optimal	25.3	18.2	36.8	19.7
Low impact	Most optimal	33.8	14.9	31.7	19.6
High impact	Most optimal	51.6	16.2	21.2	11.1

Scenario 4: *Blackside dace response to multiple stressors*

Table 2.2 demonstrates that combinations of the less influential nodes (from sensitivity analysis; Figure 2.3), such as drought, beaver activity, and logging with BMPs, still do not predict highly negative results for blackside dace populations. In contrast to this, if drought were to occur in a watershed containing low or high impact mining, blackside dace populations are predicted to incur negative trends with more probability than positive trends (Table 2.3). In fact, combining mining with just one other sub-optimal node state predicts a more than one-third probability that blackside dace will become locally extinct over five years in all instances (Table 2.3). The influence of mining on the population response can be most strikingly demonstrated by the prediction that the presence of low impact mining (with all other nodes being set to optimal) had a more negative influence on blackside dace populations than if mining was absent and all other input nodes were set to the least optimal states (Table 2.4).

Discussion

The objective of this project was to improve recovery management of the blackside dace by creating a structured decision model based on current ecological knowledge about the species. I accomplished the objective by constructing a BBN, providing a quantitative framework that can describe potential changes to the system, both human and environmental. By creating a model that is quantitative, managers can compare predictions with real world outcomes, making the model testable. It is important to create testable models in order to investigate expert belief on which the model is based, refine model structure to better represent actual outcomes and update ecological knowledge. By creating a model that is comprehensive, managers can apply the model to any blackside dace population across the range of the species, making the model transferable. Transferable models are important because they are useful to many agencies and investigate broad ecological conditions. Most importantly, by explicitly describing an influence diagram for the recovery of the blackside dace and parameterizing the diagram in a BBN framework, important ecological relationships and conditions have been effectively communicated, making the model transparent. Model transparency is important because it fosters communication amongst stakeholders and allows the model to undergo peer review.

I demonstrate that the model is both testable and transferable in Chapter 3 by applying the model to two different stream populations and quantifying unique predictions at those sites. Chapter 3 also demonstrates the ability to make explicit predictions about management decisions that can be compared to real world outcomes. Model transparency was demonstrated here in Chapter 2 by communicating the model development process, the structure and ecological relationships within the model, and the analysis results.

An important application of model analysis is indicating areas that warrant future research and discussion. For example, the large influence of conductivity on blackside dace persistence is largely supported by habitat models (Black 2007; Jones 2005), but both authors suggest that conductivity may only be a surrogate for another detrimental ecological phenomenon, such as increased heavy metal runoff. Although mine drainage is known to be associated with heavy metals (Gray 1997; Petty & Barker 2004) and have both lethal and sublethal effects on fish (Henry et al. 1999), this relationship has not yet been investigated for blackside dace. Additionally, natural variations in the conductivity of streams in the Upper Cumberland River drainage were not described. Environmental factors, such as geologic limestone deposits, are known to increase stream conductivity levels (Best 1997; Sear et al. 1999; Wooten et al. 1998). Determining whether blackside dace inhabit streams with limestone bedrock and increased conductivity could offer vital information to management. If dace avoid streams with limestone bedrock because of elevated conductivity, the historic range of blackside dace may currently be overstated. If dace inhabit these streams despite elevated conductivity, it would indicate that conductivity alone is not as important as previously believed. Because conductivity is one of the most influential variables in the model, it is advised that increased research be placed on understanding the true biological relationship between conductivity and blackside dace persistence.

Refining model relationships to more accurately describe ecological factors is also an important step in the decision modeling process. Within the blackside dace model, some changes to environmental input states may more effectively describe how the environmental variables are affecting blackside dace. Currently, beaver presence is described in the model as being either ‘present’ or ‘absent’. However, this does not effectively convey the legacy effect that beaver colonization has on stream habitat structure. Beaver alter aquatic habitat by such aspects as increasing channel width, opening riparian canopy, and altering flow regimes (Naiman et al. 1988). Alterations by beaver have temporal effects to aquatic habitat, such that stream habitat may differ one year, five years and fifteen years after beaver have colonized the area (Naiman et al. 1988). Rather than classify beaver as present or absent, the model may be improved by setting the states of beaver activity based on the number of years since beaver colonized a stream, with zero indicating beaver absence.

Changes to the definition of average streamflow would offer similar improvements. Rather than base streamflow at one snapshot in time, it would be more ecologically accurate to describe the compounding effects of multiple years of drought. Consecutive years of drought have different impacts on fish communities than seasonal droughts (Lake 2003) and may cause blackside dace to alter habitat usage as well.

Potential changes to the model highlight the ability for peer review and criticism of the model to be quickly adapted. Establishing a recovery plan for blackside dace in which new goals are quantified by this model is certainly possible. New recovery goals could be defined based on the probability of populations becoming locally extirpated. One such goal might read: “At least 3 streams in each of 8 sub-basins must always have a less than 15% probability of local extirpation over the next twenty years”. In this instance, a new model, based on a twenty year time period would need to be constructed.

Future work

Peer review and refinement is an important part of the decision modeling process. Following Marcot et al. (2006b), the current stage of our project represents the completion of an alpha level model. However, before an alpha-level model is implemented, it is recommended that the model undergo a formal peer review process to ensure credibility and effectiveness (Marcot et al. 2006b). Plans have been made to send the model to both BBN and blackside dace experts in order to receive independent agreement that the model is mathematically valid and contains appropriate ecological relationships.

Our model describes a five-year time period in order to focus on short timescale effects. However, longer time period analysis may be important. This can be accomplished by creating models that describe different time scales for the management outcome node. The model presented here could be adapted by parameterizing new conditional probabilities for population response states describing another time period of interest. For example, if predictions for population state in twenty years were needed, new conditional probabilities could be constructed, representing the expected twenty year population response, while not changing any other variables.

Conclusion

The implementation of this model provides managers with a quantifiable prediction of blackside dace population response to external influences, which will assist in recovery decision making. Conflicts between human land use and blackside dace can now be evaluated using a current understanding of the system rather than being guided by an understanding of the system twenty years ago.   Future scientific discoveries and associated data can be assimilated into this model, maintaining the model's usefulness. This modeling framework improves the *current* recovery management of blackside dace and will also lead to a more effective *future recovery management* system.

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CHAPTER 3

IMPROVING IMPERILED SPECIES MANAGEMENT THROUGH SPATIALLY-EXPLICIT DECISION TOOLS[1]

[1] McAbee, K., S. Albeke, and N. Nibbelink. 2008. P. Bettinger, K. Merry, S. Fei, J. Drake, N. Nibbelink, and J. Heppinstall editors. Proceedings of the 6th Southern Forestry and Natural Resources GIS Conference. Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA.
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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. I 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 & 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 2004;

Hanski et al. 1995) and transformation of ecosystem properties through the introduction of non-native species (Canonico et al. 2005; Kolar & 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 3.1) (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 (US 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 & 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 & Contributors 2005; Starnes & Starnes 1978; US 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 the threat of further decline is imminent because land use practices continue to affect population survival at individual sites (Mattingly & Contributors 2005; US Fish and Wildlife Service 1987).

Table 3.1. 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 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 (US 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 (US 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

I 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. I 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 (chapter two).

I 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). I 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

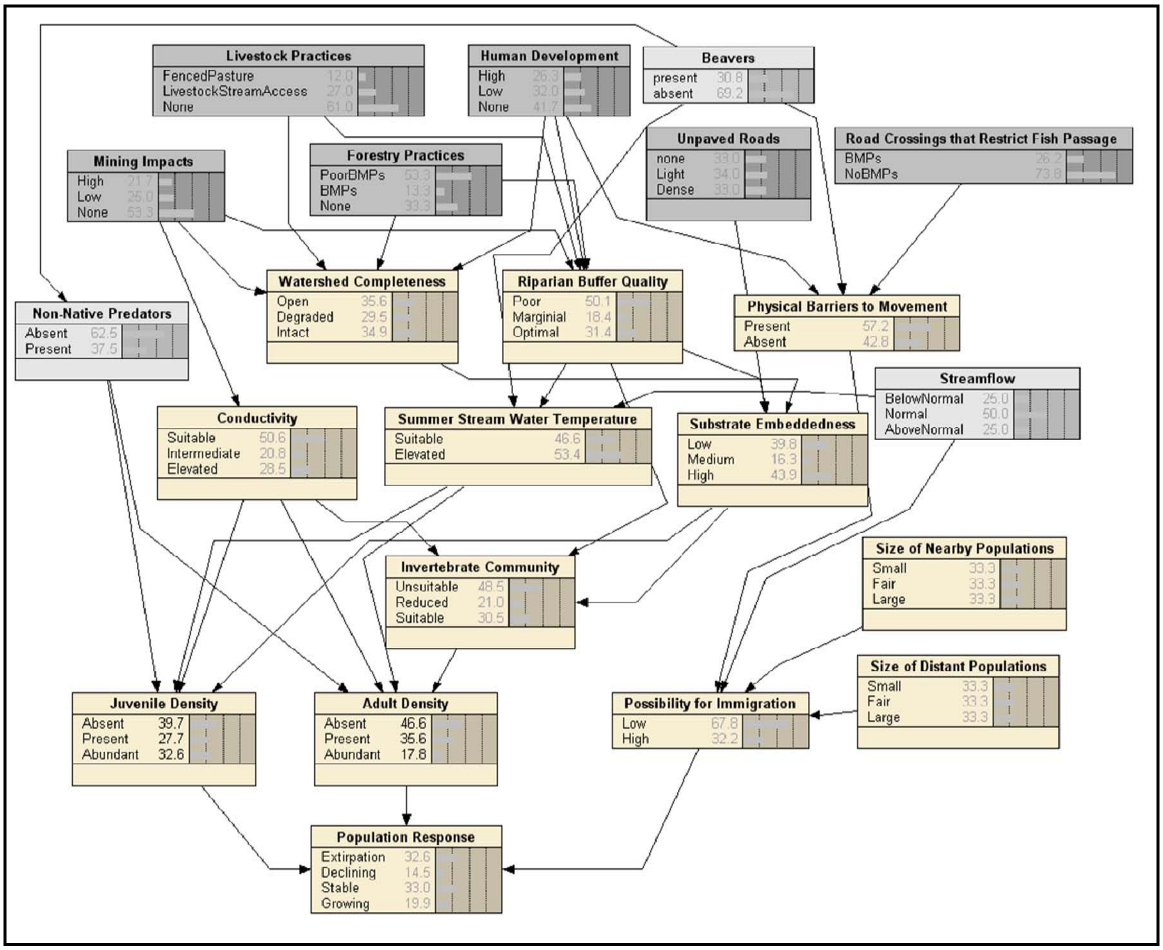
I facilitated the creation of a BBN describing the dominant characteristics thought to influence blackside dace population responses (Figure 3.1). The model was developed over a four month period (December 2007 to March 2008) by a group of scientists and managers with extensive species knowledge (see 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 3.1; 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 five-year time series because blackside dace life spans are approximately three to four years (Starnes & Starnes 1978). Therefore a population with no reproduction could reasonably be expected to become locally extirpated in five years. I 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 3.2) (Marcot et al. 2006). Each member of the model development team parameterized CPTs based on their expert

Figure 3.1. Bayesian belief network demonstrating the ecological influences on blackside dace population response. Overall model structure demonstrates that human (dark grey) and environmental (light grey) inputs influence ecological variables that shape the response of local blackside dace population response.



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, I analyzed only one population at a time. Therefore, the input nodes

Table 3.2. Conditional probability table (CPT) for summer stream water temperature node. Within in a BBN, the CPT demonstrates the probability of a child node being in a certain state, based on all combinations of the parent nodes.

Combination of parent node states			Probability of summer stream water temperature being in a particular state	
Streamflow	**Riparian buffer quality**	**Beaver presence**	**Suitable**	**Elevated**
BelowNormal	Poor	Present	9.4	90.6
BelowNormal	Poor	Absent	15.0	85.0
BelowNormal	Marginal	Present	23.4	76.6
BelowNormal	Marginal	Absent	31.0	69.0
BelowNormal	Optimal	Present	33.4	66.6
BelowNormal	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
AboveNormal	Poor	Present	53.0	47.0
AboveNormal	Poor	Absent	61.6	38.4
AboveNormal	Marginal	Present	58.8	41.2
AboveNormal	Marginal	Absent	66.0	34.0
AboveNormal	Optimal	Present	66.0	34.0
AboveNormal	Optimal	Absent	79.0	21.0

(human and biological inputs in Figure 3.1) were attributed with known states (or a 100% frequency) for each population.

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 the alpha level model are human land use inputs (mining, urbanization, etc). The working group defined these nodes using data requiring on the ground site analysis (BMP usage, etc) for their own management purposes (Appendixes A & B). However, GIS data analysis can substitute for on the ground analysis by deriving similar concepts from available spatial data. For this analysis I did not use the input node state definitions described by the working group because a complete site survey demanded too much sampling effort. Instead, I kept the same state classifications, but defined them according to publicly available spatial data. For example, rather than defining mining impacts based on Best Management Practice (BMP) usage (working group definition) I define mining impacts as the percentage of upstream watershed under mining permits.

In order to collect consistent input data for the entire study area, I calculated land use conditions using GIS software ArcGIS 9.2 (ESRI 2005) (described in GIS Data Development section). I 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, I 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.

GIS Data Development

Spatially-explicit population analyses may be performed if input conditions are known for unique geographic locations. Therefore, I 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 & 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 associated upland watershed conditions, unique watershed polygons were created (Figure 3.2). Sample locations taken from Mattingly and Contributors (2005) were snapped to the appropriate stream reach in the National Hydrography Dataset (NHD) (US Geological Survey 2007) using route events in ArcMap software (ESRI 2005). Direct upstream watersheds were delineated for each population site using the ArcHydro 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 (US 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.

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

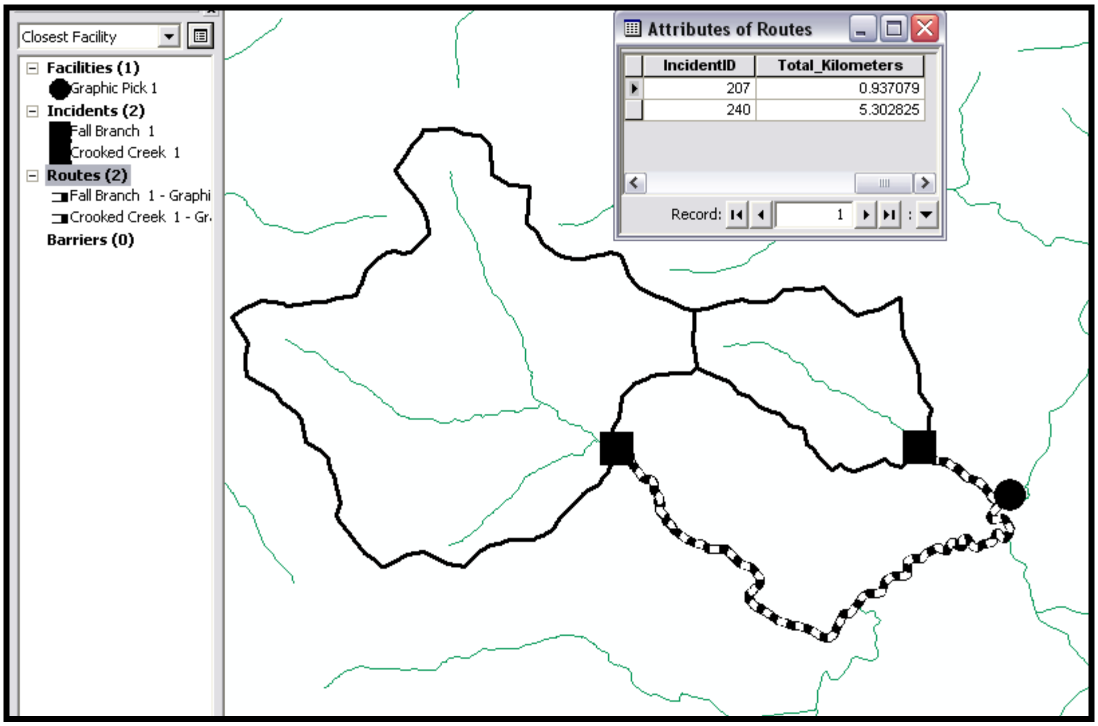
Streetmap data (ESRI 2005). Calculated metrics include percent of watershed under mining permits, percent of watershed urbanized, percent of watershed pasture, number of logging inspection sites in watershed, well density, and road crossings over streams (Table 3.3). The percentage of watershed under 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 I 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 blackside dace 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.

I calculated the size 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, I 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. I converted the NHD stream layer into a Network Dataset and created a new Closest Facility for analysis purposes (Figure 3.2). Initially, one population was added as a Facility and the second was added as an Incident. Solving for this route provided the shortest stream path between two populations. However, upstream movements are calculated with a distance of zero, making the total distance incorrect. Therefore, I 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 was 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.

Figure 3.2. Visual description of GIS methods used to calculate distance between 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. Upstream watershed boundaries are shown for each population in black.



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, I 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, I first created a geodatabase to store all data necessary for site description and BBN analysis. I 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, I demonstrate how the BBN can be used to analyze both current population conditions and future 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 (US 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 Davis Branch. 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 3.3). 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

Table 3.3. Land use condition metrics based on GIS analysis of direct upstream watersheds for two blackside dace populations. Site conditions are similar for human land use inputs, but strikingly different for environmental inputs.

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

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, I 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 I 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 3.4). 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.

Table 3.4. Expected population response for Davis Branch based on current conditions and conditions following a beaver removal program. Establishing a beaver removal program at Davis Branch has little impact on the predicted five year population response.

Population response state	Current conditions (%)	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 3.5. Expected population response for Big Lick Branch based on current conditions and conditions following low impact mining. Allowing low impact mining within the upstream watershed of Big Lick Branch has a strong negative impact on the predicted five year population response.

Population response state	Current conditions (%)	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

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 3.5). 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.

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. I 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, I may facilitate improved management of a threatened species.

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CHAPTER 4

CONCLUSIONS

This thesis presents a conceptual model supporting structured decision making for the federally threatened blackside dace (*Phoxinus cumberlandensis*). The model was constructed using the fundamental steps of decision modeling described by Clemen (1996): 1) identify and structure problem; 2) create a logical framework; and 3) refine decision elements. The first two steps were described in Chapter Two, in which I documented the current ecological understanding of the system in a Bayesian belief network (BBN) by working with species experts. I chose this modeling framework because BBNs quantitatively couple expert opinion with empirical data, communicate ecological influences clearly, and provide a graphical format for influence diagram construction (Marcot et al. 2001; Marcot et al. 2006; Nyberg et al. 2006). Chapter Three demonstrated how the model can be applied in a testable and transferable manner across the range of the blackside dace. Model analysis presented in Chapter Two provided information to guide future blackside dace ecological research and model refinement. By creating a transparent model that is updateable, managers can incorporate dynamic explicit science (Boersma et al. 2001) into future recovery objectives for blackside dace.

Challenges

Because this process is a multi-stakeholder scientific collaboration, unique challenges were encountered. Working with many stakeholders mandated well thought out time management for the each step of model creation. In order to preserve momentum of the project, meetings needed to be scheduled in relatively quick succession. However, stakeholders had to complete intermediate assignments and return them to facilitators well before each new meeting in order for the meetings to be effective. Several times during the process, meetings had to be postponed because participant responses were not received by the facilitators with enough time to summarize or analyze. Furthermore, participants could easily misunderstand assignments or have questions about specific details. To circumvent frustration amongst stakeholders, consistent contact with participants was required. Consistent conversations with participants maintained their interest, resolved their misunderstandings and emphasized their importance to project success.

An additional challenge was managing the scientific opinions of a wide variety of participants. This project was fortunate to avoid large contention about ecological effects, variables to include, etc. Individual participants offered some variations to the model presented in this thesis, but were willing to accept group consensus if it diverged from their ideas. Potential solutions to large dissention from group consensus are the construction of competing BBN models (Nyberg et al. 2006) or the inclusion of multiple system models into a single BBN (Conroy et al. 2008).

Ultimately, the greatest challenge to successful implementation of this project rests on future model employment and refinement. The model described here represents the current understanding of the blackside dace ecological system based largely on expert opinion. For it to be truly useful as a long-term management tool, the model's scientific foundation (its structure and parameterization) must be constantly re-evaluated. It is intended that this model be questioned, refined, and altered in the future, because without these steps, this model will become obsolete.

Successful Implementation

Many aspects of the model make it immediately applicable to various stakeholders. For example, a transparent model is useful for communicating the ecological relationships that affect blackside dace. The model also provides quantitative predictions which can be used as justification for or against future decisions, such as those described in Chapter Three.

Model analysis presented in Chapter Two demonstrates the relative influence of inputs on the chosen management outcome (predicted five year population response). Sensitivity analysis and scenario building demonstrated that mining practices is predicted to be the most influential input, while other inputs seem to have less substantial impacts. The smaller influence of other input nodes may serve as a prognostication that blackside dace are a robust species to certain stressors, even in combinations.

The importance of mining is largely based on the influence of stream conductivity because mining is currently the only input that affects conductivity. While the influence of stream conductivity on blackside dace presence has empirical support from habitat modeling (Black 2007; Jones 2005) the underlying ecological cause is largely unknown. The combination of high influence on outcomes and little empirical data suggest that effects of conductivity warrant future investigation. Guidance on future research needs is one constructive aspect decision analysis can offer to imperiled species recovery.

Another positive aspect of decision analysis is the ability to demonstrate how certain management decisions would affect specific locations. Therefore, I developed GIS methods to collect spatially-explicit data for 52 local stream populations and attributed BBNs for each stream with this data (Chapter Three). Spatially-explicit management scenarios were then applied to two streams as examples, Davis Branch and Big Lick Branch. The BBN revealed that a beaver removal program would not substantially improve predicted five year population response for Davis Branch. In contrast, BBN results indicate that mining operations upstream from Big Lick Branch were predicted to have a negative impact on the blackside dace population over the same length of time. Altering input states to evaluate spatially-explicit management scenarios illustrates how this modeling approach can be explicitly transferable.

Comparing predictions of management decisions to actual outcomes is a central tenant to refining the model. Model predictions from Chapter Three suggested that there was low probability of local extirpation under the current conditions at Davis Branch and that beaver removal would not greatly change the results. However, since Beaver first colonized Davis Branch in 1994, habitat structure has changed dramatically and in 2006 very few blackside dace were collected during sampling efforts (Stephens 2007). This comparison indicates that the current manner for describing beaver impacts may be inadequate. Chapter Two suggests improving the accuracy of this variable by altering the states to indicate how long beaver have inhabited the stream.

The foundation of structured decision making for the recovery of the blackside dace is established with completion of this model. This thesis demonstrates that even before explicit decision making and monitoring take place, the BBN has utility to managers and provides useful information. In fact, the development process has provided a means to summarize the breadth of blackside dace research and afforded many experts a chance to exchange ideas and data. This kind of collaboration is a powerful force in scientific research, infusing new ideas in researchers and managers alike.

Fulfillment of a complete recovery process requires further steps that could not be achieved over the course of the project. First, the model needs to be peer reviewed by independent blackside dace and BBN experts, creating more a ecologically and mathematically credible beta-level model (Marcot et al. 2006; Nyberg et al. 2006). After peer review, the model must be further tested, validated and updated with case data, following an adaptive process (Marcot et al. 2006). The refinement of the model should coincide with recovery decisions of various agencies and managers, thus directly supporting an improved recovery planning system for the blackside dace. In its current state, the model developed here merely *supports* a recovery program, it is the responsibility of blackside managers to implement the model and refine it in the future.

Conclusion

Cumulatively, this thesis offers a novel management process for the blackside dace and offers a template for revising recovery of other imperiled species. As presented here, the central tenants for improving the recovery of imperiled species are 1) acknowledging that management is occurring based on imperfect ecological information and 2) incorporating robust science into recovery decision-making as soon as it is feasible. The blackside dace BBN developed in this project accomplishes both by describing ecological system influences through structured decision analysis.

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APPENDIX A – DESCRIPTION OF NODE SET FOR BLACKSIDE DACE BBN

Node classification	Node title	Node states	Node measurement technique
Human land use inputs	Mining impacts	High	One of the enhancement guideline BMP criteria have been violated
		Low	All BMP criteria are met, but mining is taking place
		None	No mining is taking place
	Livestock practices	Fenced	Livestock grazing occurs within fenced pasture (no stream access)
		Stream Access	Livestock can access the stream
		None	No livestock grazing occurs in the watershed
	Forestry practices (Floyd & Stringer 2005)	Poor BMPs	Timber operations do not use all six protocols in Floyd and Stringer (2005)
		BMPs	Timber operations occur, but follow the protocols
		None	No timber operations occur
	Human development	High	Human activity is degrading the stream in a manner not covered by other nodes
		Low	Human activity occurs, but does not degrade the stream
		None	Human development in the watershed is very minimal
	Unpaved road density	Dense	Greater than 1 mile of unpaved road per square mile of watershed
		Light	Between 0.1 and 1 mile of unpaved road per square mile of watershed
		None	Between 0 and 0.1 miles of unpaved road per square mile of watershed
	Road crossings	BMPs	Road crossings do not create hydraulic drops acting as fish migration barriers
		Non-BMPs	Road crossings crate hydraulic drops acting as fish migration barriers
Environmental inputs	Beavers	Present	Beavers inhabit the direct upstream watershed, in any number
		Absent	Beavers are not found in the direct upstream watershed
	Non-native predators	Present	Non-native piscivores constitute greater than 5% of the sample collected
		Absent	Non-native piscivores constitute less than 5% of the sample collected
	Size of nearby populations	Small	Density of populations within 4 mi. is less than 20.5 BSD/200m
		Fair	Density of populations within 4 miles is between 20.5 and 40.5 BSD/200m
		Large	Density of populations within 4 miles is greater than 40.5 BSD/200m
	Size of distant populations	Small	Density of populations within 4-10 mi. is less than 20.5 BSD/200m
		Fair	Density of populations within 4-10 mi. is between 20.5 and 40.5 BSD/200m
		Large	Density of populations within 4-10 mi. is greater than 40.5 BSD/200m

Environmental inputs (continued)		Average monthly streamflow	Below normal	Regional stream network is in the lower quartile for 28 day streamflow
			Normal	Stream network is in the middle 2 quartiles for 28 day streamflow
			Above normal	Stream network is in the upper quartile for 28 day streamflow
Key ecological correlates	**Watershed variables**	Watershed completeness	Open	The watershed is 0 to 30% forested
			Degraded	The watershed is 30 to 70% forested
			Intact	The watershed is 70 to 100% forested
		Riparian buffer quality (Barbour et al. 1999)	Poor	The sum of the EPA rapid bioassesment riparian buffer scores for both stream banks is less than 4.5
			Marginal	The sum is between 4.5 & 17.5
			Optimal	The sum is greater than 17.5
		Barriers to movement	Present	A barrier presenting fish movement is present
			Absent	A barrier is absent
	Local stream habitat variables	Stream conductivity (Black 2007; Jones 2005)	Suitable	Stream conductivity is less than 200 µS
			Intermediate	Stream conductivity is between 200 and 240 µS
			Elevated	Stream conductivity is > 240 µS
		Summer stream water temperature (Jones 2005)	Suitable	Stream water temperature is < 18.5 °C
			Elevated	Stream water temperature is > 18.5 °C
		Substrate embeddedness (Mattingly & Black 2007)	Low	0 to 15% of the stream bed is embedded in fine sediment
			Medium	15 to 40% of the stream bed is embedded in fine sediment
			High	Over 40% of the stream bed is embedded in fine sediment
		Invertebrate diversity	Unsuitable	Less than 5.5 EPT species occur in the stream
			Reduced	Between 5.5 and 9.5 EPT species occur in the stream
			Suitable	Greater than 9.5 EPT species occur in the stream
Biological effects (Population parameters)		Density of juveniles	Absent	0 to 0.5 juvenile BSD per 200m
			Present	0.5 to 10.5 juvenile BSD per 200m
			Abundant	Greater than 10.5 juvenile BSD per 200m
		Density of adults	Absent	0 to 0.5 adult BSD per 200m
			Present	0.5 to 20.5 adult BSD per 200m
			Abundant	Greater than 20.5 adult BSD per 200m
		Possibility for immigration	Low	It is highly unlikely that immigrants would join the population
			High	It is very possible that immigrants would join the population
Management outcome		5 year Population response	Local extirpation	No BSD are present
			Decline	The population has declined by over 10%
			Stable	The population has neither grown nor declined by more than 10%
			Growth	The population has grown by over 10%

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APPENDIX B

BBN USER'S GUIDE

Level 1 – Input Nodes

Human Land Use Inputs
Human input nodes are directly controlled by human activities. They are not the decisions leading to activities, but simply the presence of an input caused by humans. This network focuses on six types of human inputs:

- **Forestry Practices**
  - This is scored based on the type of logging operations occurring in the watershed. We differentiate only between logging operations that are following the recommendations put forth in Floyd and Stringer (2005) and those that are not. Floyd and Stringer (2005) sets forth the six most important BMPs that logging activities should follow to protect blackside dace habitat. If the logging operation ignores ANY of the six recommendations in the document, this node should be scored as Poor BMPs (Floyd & Stringer 2005).
  - The recommendations are as follows:
    1. Limit crossings of intermittent and perennial streams to bridges or FORDS.
    2. Do not use stream channel as roads and do not operate equipment in the stream.
    3. Keep yards and landings outside of Streamside Management Zones (SMZs) and do not push soil (sediment) or logging slash in the stream channel.
    4. Re-vegetate roads, trails, landings, disturbed areas around crossings, and any other disturbed areas that could wash mud into the stream.
    5. Maintain 25 foot or 55 stream buffers with 50 percent of the overstory intact and ALL STREAM BANK TREES SHOULD BE LEFT.
    6. Do not block the stream with tree debris slash.
  - **States**
    - **Poor BMPs –** Logging operations in the watershed do not use ALL six protocols outlined above
    - **BMPs –** Logging operations are following ALL six of the protocols outlined above
    - **None –** No logging is occurring in the watershed

- **Livestock Practices**
  - What are the practices used in livestock farming within the watershed? If more than one practice occurs in the watershed, select the practice that

most affects the stream. This does not require a full stream survey, but rather a quality sample near the sample site.

- For example, one stream access point will alter the stream more than fenced pasture, so select Livestock Stream Access.
- **States**
  - **Fenced Pasture –** Livestock grazing occurs within fenced pastures with no stream access.
  - **Livestock Stream Access –**Livestock can access the stream easily and are able to degrade banks and/or deposit waste into streams.
  - **None –** No livestock grazing occurs in the watershed

- **Mining Impacts**
  - What are the mining impacts to the stream?
  - This node describes the usage mining BMPs for blackside dace streams. Specifically, mining operations should follow all six of the logging BMPs outlines above (for land use disturbance) and then also meet the following criteria.
  - These criteria come from the "**Guidelines for the Development of protection and enhancement plans for Blackside Dace (*Phoxinus cumberlandensis*)"** (Preliminary document: Walker and Pelren)
    1. Impoundments (including temporary sediment basins) cannot be located within intermittent or perennial streams except in atypical situations when practicable alternatives are not available.
    2. If underground mining would occur in the immediate watershed of a stream occupied by blackside dace, the underground mine will be designed to protect the integrity of the stream.
    3. Point source sediment sources (such as retention ponds) are not releasing large amounts of sediment.
    4. Riparian areas along sediment ponds and other disturbed areas along streams that would benefit from reforestation (e.g., re-mining scenarios) are to be re-planted with riparian tree species native to the local area.
    5. An appropriate combination of sediment control methods is to be used when disturbing streams during earth-moving activities (e.g., during construction of road crossings), including ephemeral channels.
  - Individuals also have the ability to mark the impact of mining as high, as long they document what specifically warranted such a decision. This could be from the scale of mining or failure to meet a BMP not listed here.
  - **States:**
    - **High –** There is high impact from mining, because one of the BMP criteria has not been met.
    - **Low –** There is low impact from mining, because all of the criteria have been met.
    - **None –** No mining occurs within the watershed

- **Human Development**
  - This node analyzes the impact that human development has on the stream, outside of the impacts covered in other nodes. In general, we are referring to urbanization, construction, etc.
  - For human impact to be scored as high, humans would have to be causing change to the stream that parallels a BMP infraction from the other nodes.
    - For example, a house that has removed all riparian vegetation and is allowing sediment from their driveway into the stream.
    - Similarly, any construction that does not meet BMPs would be scored as high.
  - For human impact to be scored as low, human activity would be present in the watershed, but actions would not degrade the stream or the activites are following all BMPs for that action.
  - **States**
    - **High –** Human development is greatly degrading the stream in a manner not covered by the other nodes (logging, mining, agriculture, roads).
    - **Low –** Human development occurs, but in a manner that does not degrade the stream heavily.
    - **None –** Human impact on the watershed is very minimal.

- **Unpaved Road Density**
  - This node describes the density of unpaved roads in the watershed of the sampling site. This node can be calculated with either GIS tools (aerial photos, etc.) or a driven survey of the roads (to calculate mileage).
  - Units of the node are miles of unpaved road per square mile of watershed
  - **States**
    - **None –** 0 to 0.1 miles of unpaved road per $mile^2$ of watershed
    - **Light –** 0.1 to 1 miles of unpaved road per $mile^2$ of watershed
    - **Dense –** greater than 1 miles of unpaved road per $mile^2$ of watershed

- **Road Crossings**
  - Describes the type of road crossings that occur at streams. Specifically, we are focusing on the ability of fish to migrate through these crossings. Crossings that would impede the movement of aquatic life, specifically, BSD, would include hydraulic drops, very low flows through crossings at typical stream levels, and highly unnatural substrate (such as metal culverts with no sediment).
  - **States**
    - **BMPs –** Road crossings do not result in hydraulic drops or act as an impediment to movement of aquatic life.
    - **No BMPs –** Road crossings create impediments to the movement of aquatic life.

Environmental Input Nodes
Environmental input nodes are inputs resulting from processes not directly controlled by humans, such as climate and ecological interactions. This network focuses on one climate input and two biological nodes.

- **Stream flow**
  - This node describes the flow levels for streams in the blackside dace region. Rather than taking a single stream measurement, this node is parameterized to describe the regional water flow compared to historical averages. To determine the state, users should use the USGS stream flow data found on the USGS website at http://water.usgs.gov/waterwatch/ . Specifically, this node is parameterized using the "28-day average streamflow compared to historical streamflow for the day of the year (Kentucky)" map. This map is updated daily and provides easy to interpret data that has already been compared to historical conditions and separated into percentiles. For more information, visit the USGS water watch website (USGS 2008).
  - To give a condition to a sampled stream, users should determine which station or set of stations are closest to the sampled stream and attribute the sample site based on the conditions at those nearby gauging stations. By placing the mouse cursor over an individual station on the map, station name and integer percentiles can be displayed.
  - **States**
    - **Below Normal –** The regional stream network is in the lower 25% percentile (0-24) for 28-day average streamflow. Currently this includes the red and orange stations on the map.
    - **Normal –** The regional stream network is in the middle 50% percentile (25-75) for 28-day average streamflow. Currently this includes the green stations on the map.
    - **Above Normal -** The regional stream network is in the upper 25% percentile (76-100) for 28-day average streamflow. Currently this includes the light and dark blue stations on the map.

- **Beavers**
  - This node describes the presence of beavers in the watershed being sampled. Presence can either be known through visual confirmation while sampling, historical knowledge, or reported sightings.
  - **States**
    - **Present –** Beaver inhabit the watershed (in any number)
    - **Absent –** No beaver inhabit the watershed

- **Non-Native Predators**
  - This node describes presence of non-native piscivores in sampling effort.
  - **States**
    - **Absent –**Non-native piscivores constitute less than 5% of the fish sample.
    - **Present –**Non-native piscivores constitute more than 5% of the fish sample.

Level 2 – Key Ecological Correlates

2a – Associated Upland Landscape Conditions

Physical Landscape nodes describe the condition of the surrounding watershed of blackside habitat. These nodes describe the landscape's response to human and environmental inputs and influence BSD habitat directly.

- **Watershed Completeness**
  - This node describes the percent of watershed (upstream of the blackside dace habitat) that is forested. Watershed boundaries will be created using ArcGIS and calculated for only the stream that currently harbors BSD. All non-forested land use (logging within the last 5 years, agriculture, urbanization, surface/mountain top mining, & roads) will be aggregated into one classification.
  - Units are Percent Forested
  - **States**
    - **Open –** The watershed is 0 to 30% forested
    - **Degraded –** The watershed is 30 to 70% forested
    - **Intact –** The watershed is over 70% forested

- **Riparian Buffer Quality**
  - This node describes the quality of the riparian buffer for BSD inhabited streams. Using the EPA rapid bio-assessment protocol, field teams score the width of riparian area on both the left and the right bank. Each bank is scored on a scale of 0 to 10, with 10 being a wide, non-impacted buffer zone and 0 being a thin, degraded buffer zone (Barbour et al. 1999; Kentucky Division of Water 2002). When these scores are added together, BSD streams will have a riparian buffer quality score between 0 and 20. This scoring system analyzes the vegetative condition, sediment inputs, etc for approximately 60 feet on each side of the stream.
  - For a more detailed description, read page 5-30 in the EPA Rapid Bio-assessment Protocol (Barbour et al. 1999) or page 28 of the Methods for Assessing Biological Integrity of Surface Waters in Kentucky (Kentucky Division of Water 2002)
  - Units are EPA rapid bio-assessment protocol scoring for both sides
  - **States**
    - **Poor –** The sum is less than 4.5
    - **Marginal –** The sum is between 4.5 and 17.5
    - **Optimal –** The sum is greater than 17.5

- **Physical Barriers to Movement**
  - This node describes if a barrier that would prevent BSD movement is present within in the watershed. These include beaver dams, culverts, and any other structure that would prevent dace **either leaving or entering** the inhabited stream.
  - A complete survey is not needed, but road crossings should be checked.

- **States**
  - **Present –** A barrier is present
  - **Absent –** A barrier is absent

2b - Local Stream Parameters

These nodes describe blackside dace habitat, including water, streambed, and food. They directly affect the health of population dynamics through individual interaction. For example, an increased water temperature may kill 55% of individuals in a stream.

- **Conductivity**
  - This node describes the conductivity level for stream water harboring BSD.
  - These states are based on empirical research from multiple studies conducted at TTU from 2000 to 2007 (Black 2007; Jones 2005)
  - Units are micro-Siemens
  - **States**
    - **Suitable –** Less than 200 uS
    - **Intermediate –** Between 200 and 240 uS
    - **Elevated –** Greater than 240 uS

- **Summer Stream Temperature**
  - This node describes the stream water temperature in summer months. Summer stream temperature is known to be a strong predictor for BSD presence from (Black 2007; Jones 2005)
  - This temperature should be taken during the hours of 12 and 4 pm, during the summer months.
  - Units are degrees Celsius
  - **States**
    - **Suitable –** The temperature is below 18.5 C
    - **Elevated –** The temperature is greater than 18.5 C

- **Substrate Embeddedness**
  - This node describes the level to which large cobble is embedded by fine sediments in BSD inhabited pools. This metric is a visual survey conducted over 10 areas within a 200m reach, covering all of the habitat types (pool, riffle, run, etc.). Overall metric for the site will be an average of the site values. The scoring will follow the Bain and Stevenson (1999) classification of embeddedness, with fine sediment defined as materials less than 2mm in diameter: sand, silt, and clay.
  - A description of a similar measurement can be found on page 5-13 of the EPA Rapid Bio-assessment protocol (Barbour et al. 1999)
  - **State**
    - **Low –** 0 to 15% of the stream bed is embedded in fine sediment
    - **Medium –** 15 to 40% of the stream bed is embedded in fine sediment
    - **High –** Over 40% of the stream bed is embedded in fine sediment

- **Invertebrate Diversity**
  - This node describes the health of the winter invertebrate community in BSD inhabited streams. Sample should be taken during the winter months, following the Protection and Enhancement Plan guidelines.
  - Units are the number of EPT species found in macro invertebrate sampling
  - **States**
    - **Unsuitable –** less than 5.5 EPT species occur
    - **Reduced –** between 5.5 and 9.5 EPT species occur
    - **Suitable –** more than 9.5 EPT species occur

Level 3 – Biological Effects

Immigration Factors
These nodes describe characteristics of nearby populations that influence the ability of individuals to emigrate to the local population under investigation. These nodes represent combined characteristics of population size and proximity.

- **Size of Nearby Populations**
  - This node represents to total estimated population density of all populations within 4 stream miles. BSD have been shown to travel 4 stream miles in one season (Detar 2004), therefore the likelihood of an immigration event is highest within this radius.
  - **States**
    - **Small –** Combined density of all populations within 4 miles is less than 20.5 individuals
    - **Fair –** Combined density of all populations within 4 miles is between 20.5 and 40.5 individuals.
    - **Large –** Combined density of all populations within 4 miles is greater than 40.5 individuals.

- **Size of Distant Populations**
  - This node represents to total estimated population density of all populations within 4 and 10 stream miles. Over the course of a five year period, BSD are expected to travel more than 10 stream miles with low probability.
  - **States**
    - **Small –** Combined density of all populations between 4 and 10 miles is less than 20.5 individuals
    - **Fair –** Combined density of all populations between 4 and 10 miles is between 20.5 and 40.5 individuals.
    - **Large –** Combined density of all populations between 4 and 10 is greater than 40.5 individuals.

Population Characteristics
These nodes describe the population of BSD at the stream under investigation.

- **Juvenile Density**
  - This node represents the size of the juvenile BSD population in the stream under investigation. Juveniles are defined as individuals that are less than 40 mm standard length when collected.
  - The units for this node are individuals per 200m of sampled stream.
  - **States**
    - **Absent –** 0 to 0.5 BSD per 200m of sampled stream
    - **Present –** 0.5 to 10.5 BSD per 200m of sampled stream
    - **Abundant –** Greater than 10.5 BSD per 200m of sampled stream

- **Adult Density**
  - This node represents the size of the adult BSD population in the stream under investigation. Adults are defined as individuals that are greater than 40 mm standard length when collected.
  - The units for this node are individuals per 200m of sampled stream.
  - **States**
    - **Absent –** 0 to 0.5 BSD per 200m of sampled stream
    - **Low –** 0.5 to 20.5 BSD per 200m of sampled stream
    - **High –** Greater than 20.5 BSD per 200m of sampled stream

- **Possibility for Immigration**
  - This is a completely un-measurable node, simply representing the expert's belief that immigration can contribute to the population in a meaningful manner.
    - Therefore, it is not the belief that one immigrant can show up, but rather the belief that many immigrants can enter into the sampled stream population and contribute genetically.
  - Therefore the **States of Low and High** are simply states to match the idea that it is unlikely that immigrants will contribute genetically (**Low**) or it is likely that immigrants will contribute genetically (**High)**
  - This node will not be part of the adaptive management regime unless more robust sampling methods are employed. If more robust methods are employed, the BBN should be updated to more effectively incorporate that data into the model.

Level 4 - Management Objective / Biological Outcome

- **Population Response**
  - The overall population response in the model is the change in population size over a 5 year period. We chose 5 year period because BSD have a maximum life span of 3-5 years. Therefore, a 5 year period without reproduction could result in local population extirpation.

- **States**
  - **Extirpation – S**amples indicate that BSD no longer occur in the stream reach
  - **Decline –** The population declined by >= 10% over five years
  - **Stable –** The population has neither grown nor declined by more than 10% over the five year period.
  - **Growth –** The population increased by >= 10% over five years

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APPENDIX C

MEMBERS OF THE BLACKSIDE DACE WORKING GROUP

Member	Organization
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Tyler Black	Tennessee Tech University
Michael Floyd	US Fish and Wildlife Service (Frankfort, KY Field Office)
David Pelren	US Fish and Wildlife Service (Cookeville, TN Field Office)
Steve Bakaletz	National Park Service (Big South Fork NRRA)
Craig Walker	Office of Surface Mining
Ed Scott	TVA (retired)
Doug Stephens	Kentucky Game and Fish (retired)
Jim Williams	Kentucky Game and Fish
Matt Thomas	Kentucky Game and Fish
Brena Jones	North Carolina Wildlife Resources
Trisha Johnson	Cumberlands HCP