SUPPORTING CONSERVATION DECISION MAKING FOR IMPERILED CATOSTOMID FISHES IN THE SOUTHEASTERN U.S.

by

AN CHEE HSIUNG

(Under the Direction of Brian Irwin)

ABSTRACT

Making management decisions for conservation of imperiled species requires consideration of both social and ecological factors related to the decision context. In this dissertation, I developed tools to help support conservation decision making for two imperiled fishes – Robust Redhorse (*Moxostoma robustum*) and Sicklefin Redhorse (*Moxostoma* sp.) – in the southeastern U.S. Chapter 1 introduces the context of the studies and sets up the dissertation structure. In Chapter 2, I constructed a population estimation model to help inform managers of the population status and key parameters of Sicklefin Redhorse in Brasstown Creek, GA. The model analyzed data collected by two different sampling methods – fyke nets and PIT antenna, thereby helping demonstrate the efficacy and trade-offs of using the different sampling methods. In Chapter 3, I worked with members of the Robust Redhorse Conservation Committee to go through a structured decision-making process involving facilitated workshops, population estimation modeling, and population viability analysis to help stakeholders evaluate the probability of potential management scenarios achieving management objectives. The process used in Chapter 3 and results from the management evaluation could help the RRCC develop an adaptive management framework for conserving the species in the long-term. Learning is an important aspect of species conservation and management. In Chapter 4, I used the Robust Redhorse Conservation Committee as a case study to investigate how a diverse group of stakeholders can learn together through collaboration and deliberation (i.e., social learning). Through analysis of documents and interviews, I identified learning outcomes from the RRCC, including gaining knowledge about the species and ecosystem being managed (instrumental learning), and relationship and trust building (relational learning). I also identified several factors affecting social learning among RRCC members, such as diversity of the stakeholder group, quality and frequency of stakeholder interactions, and quality of information exchange and deliberations. Chapter 5 offers summaries of key findings from Chapters 2–4 and my reflections on conducting integrative conservation research.

INDEX WORDS: Structured decision making, Catostomidae, population viability analysis, population modeling, adaptive management, social learning

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DEDICATION

To all those who believed in me in the past, present, and future to achieve everything I set my mind on.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

Solving today's environmental problems requires consideration of diverse stakeholder values while integrating analytical tools from across disciplines (Bennett et al. 2017). Interdisciplinary mixed-methods research has the potential to provide more holistic views of complex environmental issues (Kinnebrew et al. 2021). Conservation of endangered species lends itself to be examined through multiple lenses as it is situated in the intersection of stakeholder values, policy, and management processes (Wallace et al. 2002; Brignon et al. 2019). In this research, I employed both quantitative and qualitative approaches to contribute to conservation and management of imperiled fish species. Specifically, I focused on the decision-making and learning processes of collaborative conservation efforts of fishes in the family Catostomidae.

DISSERTATION CONTEXT

Conservation of Catostomid fishes

The southeastern U.S. hosts a high diversity of freshwater fish species, many of which are threatened due to impacts from anthropogenic developments and land use (Warren and Burr 1994; Warren et al. 2000). Among the native fishes in the southeast, species in the family Catostomidae are particularly vulnerable to environmental impacts from human disturbances, yet management is uncertain because little is known about the life history of species in this group. Catostomidae is a diverse group of fishes that contains at least 76 species, 44 of which are found in the Southeast (Cooke et al. 2005). Beyond the common characteristics shared by species within family Catostomidae, distinguishing one Catostomid species from another without using identifying characteristics such as lip features and number of fin rays and lateral line scales can be difficult. Catostomids play important ecological roles, such as affecting invertebrate community compositions through grazing and contributing to nutrient cycling through egg production (Cooke et al. 2005). However, they are little studied compared to economically important game fish, thus conservation status is unknown for many of the species (Cooke et al. 2005).

Some common threats facing Catostomids include hydropower dams that obstruct access to spawning habitats, urban and agricultural run-off that degrades habitats and creates sedimentation, and predation by introduced exotic species to freshwaters (Cooke et al. 2005; Grabowski and Isely 2006; Jennings et al. 2009). Catostomid fishes reside in water bodies that are important to diverse resource users who use the rivers and surrounding landscapes for a wide array of purposes such as hydropower dam operation, agriculture, residential development, and recreation. Therefore, conservation of Catostomids requires a holistic approach that considers diverse interests of stakeholders. Further, given the complex nature of the conservation problem, researchers have advocated for adopting adaptive management to develop a defensible and sustainable management decision-making process when evaluating potential management actions (Cooke et al. 2005). This dissertation focuses on two Catostomid species found in the southeast.

Sicklefin Redhorse

Sicklefin Redhorse (*Moxostoma* sp.) is endemic to the Little Tennessee and Hiwassee river drainages in Georgia and North Carolina (Favrot and Kwak 2018). Within genus *Moxostoma*, Sicklefin Redhorse is recognized for its elongated and falcate dorsal fin. Though Sicklefin Redhorse has not officially been described as a species, the Cherokee Indians had named it U-gii-da-tli, meaning "one feather on top" (Caleb Hickman, Eastern Band of Cherokee Indians Office of Fish and Wildlife Management, personal communication), and suckers and redhorses in general were an important food source for the Cherokee people in the region many centuries ago (EBCI Office of Natural Resources). Adult Sicklefin Redhorse prefer to spawn over cobble and gravel substrates in rivers with moderate to fast moving water (Favrot and Kwak 2018). Sicklefin Redhorse exhibit potamodromous migratory patterns (i.e., migration occurs entirely in freshwater), moving upstream to breeding habitat in tributaries in April and May when water temperatures reach 10 °C to 16 °C and return downstream to larger river habitat after they spawn (Favrot and Kwak 2018). The adult population occupying the Hiawassee River Basin spends post-spawning and winter seasons in the mainstem of the Hiawassee River and migrate into tributaries such as Brasstown Creek and Valley River in the spring to spawn. Due to its migratory behavior, Sicklefin Redhorse are especially vulnerable to dams that prevent them from accessing spawning habitats and fragment their populations (Jenkins 1999).

A Candidate Conservation Agreement (CCA) was developed in 2015 between U.S. Fish and Wildlife Service, North Carolina Wildlife Resources Commission, Duke Energy Carolinas, Tennessee Valley Authority, Eastern Band of Cherokee Indians, and Georgia Department of Natural Resources (U.S. Fish and Wildlife Service 2015). The CCA establishes a formal agreement among signatories to “cooperate on actions that conserve, manage, and improve Sicklefin Redhorse populations range-wide with the goal of working to preclude the need to list the species under the Endangered Species Act of 1973” (U.S. Fish and Wildlife Service 2015). Additionally, the Sicklefin Redhorse Conservation Committee (SRCC) was formed to coordinate monitoring and management efforts and to share knowledge about the species and its populations among relevant stakeholders.

One of the objectives of the CCA is to re-establish populations of the Sicklefin Redhorse throughout its historic range (U.S Fish and Wildlife Service 2015). However, before initiating reintroduction programs, the SRCC prioritized monitoring of existing populations to ensure they were viable and to determine if they could serve as a source for broodstock or translocation of adults. In the Hiwassee drainage, Brasstown Creek was selected for monitoring because it contained a relatively large but unquantified population during the spawning season.

Robust Redhorse

Robust Redhorse (*Moxostoma robustum*) is another imperiled Catostomid found in rivers on the Atlantic slope of the southeastern U.S., including Georgia, North Carolina, and South Carolina. The species was originally described by Edward Drinker Cope (1870) but was considered “lost” to science until some specimens collected from the Oconee River in Georgia were identified as Robust Redhorse in the late 1980s and early 1990s. The species inhabits medium to large rivers and feed primarily on bivalves and aquatic invertebrates (Fisk et al. 2013). The reproductive ecology of Robust Redhorse is similar to that of Sicklefin Redhorse where adults make seasonal migrations between spawning and non-spawning habitats (Grabowski and Isely 2006; Jennings et al. 2010)

Populations of Robust Redhorse have been declining or remaining at low abundance for the last two decades (Zelko 2014). Several threats potentially contributed to the decline or suppress the recovery of Robust Redhorse. Migration routes (especially upstream) of many riverine fishes in North America have been obstructed by dams (Schilt 2007). There are several dams present within the range of Robust Redhorse, which could block migratory routes between spawning and non-spawning grounds and limit recruitment (Grabowski and Isely 2006). Fine sediments accumulating in spawning and rearing habitats can also affect recruitment of young-of-the-year into the population by filling the interstitial spaces of gravel substrate on which adults can lay eggs, thus reducing larval survival to emergence. Jennings et al. (2009) experimentally determined that survival to emergence of Robust Redhorse larvae decreases as the fine sediments in the gravel increases. Additionally, larvae that emerged from substrate with more fine sediments are smaller compared to those emerging from substrate with less or no fine sediments (Jennings et al. 2009). Water flow, specifically amount and timing of water availability, is another important factor affecting rearing habitat for Robust Redhorse. In experiments altering flow velocity, Robust Redhorse larvae exposed to pulsed, high-velocity water flow grew more slowly and had lower survival rate compared to fish that did not experience such flows (Ruetz III and Jennings 2000; Weyers et al. 2003). Insufficient water in the spawning and rearing habitats could also result in dewatering of redds produced by spawning Robust Redhorse in the river (Fisk et al. 2013). Similar to other long-lived sucker species, adult Robust Redhorse have a relatively high survival rate (Jennings et al. 2000). However, anecdotal accounts suggest that incidental mortality by bowfishing could negatively impact adult survival in basins where Robust Redhorse co-occur with similar-appearing carp and non-threatened sucker species pursued by local fishermen (C. Straight, U.S. Fish and Wildlife Service, personal communication).

The Robust Redhorse Conservation Committee (RRCC) was formed shortly after the rediscovery of the Robust Redhorse population in the Oconee River, GA. Established under a Memorandum of Understanding in 1995, the RRCC is a partnership among stakeholders from federal and state natural resource agencies, academic institutions, utilities, and non-profit organizations with the purpose of restoring the species and its populations within its historical range. Members of the RRCC have been engaging in monitoring and management of Robust Redhorse populations for nearly three decades. One recent goal of the Committee is to develop an adaptive management framework that will aid in conservation and management of the species.

Structured decision making

Structured decision making (SDM) is a tool natural-resource managers can use to evaluate potential management strategies based on predicted capacity to achieve management objectives. It is an "organized process for engaging multiple parties in a decision-oriented dialogue that considers both facts (from scientists and other sources) and values" (Gregory and Long 2009), and it is a process that has been widely applied in natural-resources management and biodiversity conservation (Irwin et al. 2011; Maestri et al. 2017; O'Donnell et al. 2017; Robinson et al. 2017). SDM provides a framework that allows stakeholders to explicitly identify the problem at hand and clarify objectives that need to be achieved to solve or mediate the problem. Importantly, SDM incorporates stakeholder values into the decision-making process, thus promotes transparency about how decisions are made (Brignon et al. 2019; McMurdo Hamilton et al. 2021).

Adaptive management

Adaptive management (AM) involves applying SDM to make recurring decisions based on newly emerged information about the system while attempting to reduce uncertainty. For example, managers used the adaptive management approach for the reintroduction effort of the New Zealand hihi (*Notiomystis cincta*), an endangered native bird species (Armstrong et al. 2007). Through implementation and evaluation of different management actions over 15 years, biologists and managers were able to determine the combination of nest box provision and food supplementation that was most effective at ensuring persistence of hihi populations on the Mokoia Island, New Zealand. By monitoring the population after implementing management actions and updating the population models, the researchers were able to reduce uncertainty around efficacy of each management action for the population through experimental adaptive management and moved towards more effective management actions (Armstrong et al. 2007; Canessa et al. 2016). While SDM and AM are both value-based approaches to decision making and management that make stakeholder values explicit and incorporate them in the decision-making process, traditional adaptive management focuses on technical learning, i.e., the reduction of scientific uncertainty through the making of recurrent decisions, experimentation, and monitoring system response (Williams et al. 2009; Cundill et al. 2012). However, some researchers have urged for a deeper look at how stakeholders learn through collaboration and how diverse worldviews and other factors may affect the learning process during adaptive management (Cundill et al. 2012). Learning that goes beyond individuals and becomes situated in the social/group context is considered "social learning" (Reed et al. 2010).

Social learning

In the relevant literature, the definition of social learning varies depending on which aspect of the learning process and outcome scholars choose to investigate. Some research focuses on the co-production of knowledge among individuals that was transferred to the community level during a participatory process (Muro and Jeffrey 2008) while others emphasize the social interactions that occur through collaboration and deliberation among stakeholders (Gerlak et al. 2019). Further, as part of social learning originates from transformative and organizational learning theories, some scholars use the “loop learning” framework to focus their research where single-loop learning is indicated by strategic changes under the same normative constraints, double-loop learning requires revisiting of assumptions guiding stakeholder actions, and triple-loop learning sees changes in actors’ values, world views and beliefs (Pahl-Wostl 2009; Williams et al. 2009). The application of social learning frameworks to analyzing natural resource governance has gained momentum in recent years, with numerous examples in water resource management (Pahl-Wostl et al. 2007; Borowski et al. 2008; Koontz 2014; Medema et al. 2014), forestry (Assuah and Sinclair 2019; Fernández-Giménez et al. 2019), wildfire management (Brummel et al. 2010), climate change adaptations (Baird et al. 2014; Ensor and Harvey 2015), among others. However, the process of social learning and its associated outcomes have rarely been examined under the context of threatened and endangered species conservation.

DISSERTATION STRUCTURE

Using both quantitative and qualitative tools, I address the current issues facing conservation of Sicklefin Redhorse and Robust Redhorse. First, I fill some gaps in our understanding about the population status of both species while employing population estimation models (Chapters 2 & 3). In Chapter 3, I also took a forward-looking approach while illustrating a decision-making context for Robust Redhorse population sustainability in the future through a combination of expert elicitation workshops and population viability analyses. Decision-making processes and outcomes are often mediated by stakeholder characteristics, values, and the collaboration and deliberation process. Therefore, Chapter 4 offers a unique examination of past learning process and outcomes of the RRCC and how those in turn may affect future management decision making.

Insufficient knowledge about population status of a rare species impedes biologists' ability to make informed management decisions about the species. The knowledge gap is sometimes a result of ineffective population monitoring tools. In Chapter 2, I collaborated with the SRCC to develop a population model to estimate parameters of the adult Sicklefin Redhorse population in Brasstown Creek, GA to help inform the status of the population. I did so by analyzing capture-mark-recapture data collected by the SRCC using two types of sampling gear: fyke nets for capturing and tagging fish and Passive Integrated Transponder (PIT) antenna for detecting previously tagged fish. Aside from estimating demographic processes of the population, we also sought to compare efficacy of the two sampling gear types to help inform population monitoring effort by SRCC biologists.

In Chapter 3, I present a case of structured decision making to conservation of Robust Redhorse. The overarching goal of this study was to facilitate SDM workshops with the RRCC to guide stakeholders through the process towards building a framework for adaptive management. The two main objectives related to the project goal are 1) construct a population model to estimate size stage-specific parameters for Robust Redhorse populations and 2) conduct a PVA to project Robust Redhorse populations under various scenarios to help stakeholders evaluate potential management actions. The outcomes of the SDM process could potentially be included in the eventual Species Status Assessment for Robust Redhorse to inform listing decisions for the species (Smith et al. 2018) and help stakeholders pursue adaptive management to conserve and manage the species for the future.

Chapter 4 offers a close examination of the social learning process in the context of Robust Redhorse conservation. In this chapter, I first identified evidence of social learning within the RRCC and factors affecting learning outcomes. I used a qualitative approach by reviewing annual meeting summaries produced by the RRCC and conducting semi-structured interviews with past and current RRCC members to examine whether and how the stakeholders have learned about the species, the system, as well as other members' values and perspectives.

Chapter 5 provides a summary of findings from chapters 2–4 and offers insight on how the dissertation chapters, taken together, contribute to the current body of knowledge of Catostomid fishes, as well as factors affecting learning in a diverse group of stakeholders. In this chapter, I also reflect on my experience learning to be an integrative researcher. Lastly, a goal of the Integrative Conservation PhD Program is to train its students to communicate scientific to audiences outside of academia. In chapter 5, I also present some of my experiences practicing strategic communication skills during my PhD at UGA.

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CHAPTER 2

ESTIMATING POPULATION PARAMETERS OF AN IMPERILED FRESHWATER FISH[1]

[1]Hsiung, A. C., Albanese, B., Chandler, R. B., Moore, C. T., and B. Irwin. To be submitted to *Transactions of the American Fisheries Society*.

Abstract

Sicklefin Redhorse (*Moxostoma* sp.) is a Catostomid fish endemic to Little Tennessee and Hiawassee river basins in the southern Appalachian region. The species is not yet described, but its populations are thought to be facing threats from anthropogenic developments. From 2016 to 2021, monitoring data from both physical captures from fyke net and detections of marked fish from Passive Integrative Transponder (PIT) antenna were collected to gain a better understanding of population dynamics of adult Sicklefin Redhorse in Brasstown Creek, GA to inform conservation and management decisions. We used a Jolly-Seber model to estimate annual apparent survival probability, annual population size, annual recruitment, and detection probability by gear for adult Sicklefin Redhorse. To evaluate the added value of PIT antenna as a monitoring tool, we analyzed fyke data only and compared the results to those from analyzing both fyke and PIT antenna data together. The resulting estimates of population parameters and detection probability differed, but population size showed a decreasing trend regardless of inclusion of PIT antenna data. Estimates of annual population size ranged from 122 to 225 individuals when the model included both fyke and antenna data, which were lower than the corresponding estimates when only fyke data was analyzed (601–1,328 individuals). Overall, uncertainty around parameter estimates was lower when both fyke and antenna data were included. Our demonstrated the potential information gained from using PIT antenna arrays in combination with physical captures (e.g., fyke net) to improve population inference for an imperiled freshwater fish. The results from this study provide valuable information to guide management actions for the Sicklefin Redhorse population within the Hiwassee River Basin, and our methods can be used to information management decisions on other species elsewhere

Introduction

The southeastern U.S. hosts a high diversity of freshwater fish species, many of which are threatened due to impacts from anthropogenic developments and land use (Warren and Burr 1994; Warren et al. 2000). In a review of the status of southern fishes, Warren et al. (2000) summarized that 28%, or 187 taxa, of freshwater and diadromous fish species were recognized as extinct, endangered, threatened, or vulnerable, a 125% increase in 20 years. Among the native fishes in the southeast, species in the family Catostomidae are particularly vulnerable to environmental impacts from human disturbances, yet little is known about these species. Catostomidae is a diverse family of fishes that contains at least 76 species, 44 of which are found in the southeast (Cooke et al. 2005). Catostomids play important ecological roles, such as affecting invertebrate community compositions through grazing and contributing to nutrient cycling through egg production (Cooke et al. 2005). However, they are little studied compared to economically important game fish, thus conservation status is unknown for many of the species (Cooke et al. 2005). Some common threats facing Catostomids include hydropower dams that obstruct access to spawning habitats, urban and agricultural run-off that degrades habitats and creates sedimentation, as well as predation by introduced species to freshwaters (Cooke et al. 2005; Grabowski and Isely 2006; Jennings et al. 2009).

Sicklefin Redhorse (*Moxostoma* spp.) is endemic to the Little Tennessee and Hiwassee river drainages in Georgia and North Carolina (Figure 2.1; Favrot and Kwak 2018). The fish is recognized for its elongated and falcate dorsal fin. Though Sicklefin Redhorse has not officially been described as a species, the Cherokee Indians had identified it as U-gii-da-tli, meaning "one feather on top", and Catostomids were an important food source for the Cherokee people in the region many centuries ago (Eastern Band of Cherokee Indians). Adult Sicklefin Redhorse typically spawn over cobble and gravel substrates in rivers with moderate to fast moving water (Favrot and Kwak 2018). Sicklefin Redhorse exhibit potamodromous migratory patterns (i.e., migration occurs entirely in freshwater), moving upstream to breeding habitat in tributaries in April and May when water temperatures reach 10 °C to 16 °C and return downstream to larger river habitat after they spawn (Favrot and Kwak 2018). The adult population occupying the Hiawassee River Basin spends post-spawning and winter seasons in the mainstem of the Hiawassee River and migrate into tributaries such as Brasstown Creek and Valley River in the spring to spawn. Due to its migratory behavior, Sicklefin Redhorse are especially vulnerable to dams that prevent access to spawning habitats and fragment their populations (Jenkins 1999). Further, human development in the southern Appalachian region could a negatively impact Sicklefin Redhorse populatoins. For example, while assessing aquatic communities in 36 watersheds in the Upper Tennessee River drainage, Scott (2006) found that increase in urbanization and decrease in forest cover were correlated with shifts in the local fish community from a diverse biota with more endemic fish species (e.g., Black Redhorse and Golden Redhorse) to a more homogenous community dominated by cosmopolitan species not endemic to the region.

Currently, Sicklefin Redhorse is listed as threatened in North Carolina and endangered in Georgia. A Candidate Conservation Agreement (CCA) was developed in 2015 between U.S. Fish and Wildlife Service, North Carolina Wildlife Resources Commission, Duke Energy Carolinas, Tennessee Valley Authority, Eastern Band of Cherokee Indians, and Georgia Department of Natural Resources (U.S. Fish and Wildlife Service 2015) for conservation of

Sicklefin Redhorse. The CCA establishes a formal agreement among signatories to "cooperate on actions that conserve, manage, and improve Sicklefin Redhorse populations range-wide with the goal of working to preclude the need to list the species under the Endangered Species Act of 1973" (U.S. Fish and Wildlife Service 2015). Additionally, the Sicklefin Redhorse Conservation Committee (SRCC) was formed to coordinate monitoring and management efforts, and to share knowledge about the species and its populations among relevant stakeholders.

One of the specific objectives of the CCA is to re-establish populations of the Sicklefin Redhorse throughout its historic range (U.S Fish and Wildlife Service 2015). However, before initiating reintroduction programs, the SRCC prioritized monitoring of existing populations to ensure they were viable and to determine if they could serve as a source for broodstock or translocation of adults. In the Hiwassee drainage, Brasstown Creek was selected for monitoring because it contained a relatively large but unquantified population during the spawning season. Annual monitoring began in 2016 utilizing capture-mark-recapture (CRM) data collected using physical capture methods and a Passive Integrative Transponder (PIT) antenna.

PIT antenna is a population monitoring technology that has been used in fisheries research to make inferences regarding individual movements and population dynamics (Bond et al. 2007; Hewitt et al. 2010; Raabe et al. 2014; Conner et al. 2020). PIT antennas allow biologists to collect detection data with less frequent use of invasive capture methods that could have negative impacts on fish safety and welfare (McMichael et al. 1998; Snyder 2003; Nguyen et al. 2014). Instead of physically capturing fish repeatedly with traditional CMR protocols, PIT antennas placed in the rivers within the habitat of the target populations can detect and record fish marked with PIT tags in the vicinity of the antennas.

The objective of this project was to gain a better understanding of the population status and dynamics of the Sicklefin Redhorse population in Brasstown Creek, GA. Additionally, the project aims to elucidate the effectiveness of the sampling gears used to monitor Sicklefin Redhorse populations. We aimed to estimate time-varying survival probabilities and recruitment, as well as population size and detection probabilities by different types of gear. The results will help inform management decisions made by the SRCC to conserve the species.

Methods

Study area

Brasstown Creek is a 13-km undammed tributary of the Hiwassee River Basin. It originates from Brasstown Bald in Towns County in northern Georgia and flows north through Clay County in North Carolina before joining the Hiwassee River (NCDEQ 2012). Landcover within the Brasstown Creek basin contains mostly forest (77%), but agriculture (15%) and development (6%; NCDEQ 2012) also occur. Major concerns for the aquatic community within the Hiwassee River Basin include flow regime alteration and impoundment by dams, as well as increased pollution and sedimentation from residential and commercial development (NCWRC 2015). Brasstown Creek experienced a decrease in water quality and was listed as impaired due to non-point source pollution in the mid 1990's (United States Environmental Protection Agency 2006). To address the issue, the Hiwassee River Watershed Coalition led several restoration efforts in partnership with local government agencies and private landowners that resulted in improved water quality in Brasstown Creek by 2000 (United States Environmental Protection Agency 2006). However, increased interests in exurban developments in the region could once again threaten the habitat quality for aquatic communities. Aside from Sicklefin Redhorse, Brasstown Creek contains 20 fish species, including several Catostomids such as Black Redhorse (*M. duquesnei*), Silver Redhorse (*M. anisurum*), Golden Redhorse (*M. erythurum*), and River Redhorse (*M. carinatum*) (NCDEQ 2012; Goeltz et al. 2017).

Field sampling

Monitoring of the Sicklefin Redhorse population in Brasstown Creek in Towns County, GA began in 2014. Biologists used seine nets, fyke nets, and PIT antennas placed in the river to collect CMR data. Seine data was collected from 2014 to 2016 during the spawning season (Table 2.1). Fyke netting was initiated in 2016 at a site just upstream of the North Carolina border. This site was selected to intercept Sicklefin Redhorse migrating to spawning habitat in upper Brasstown Creek.

A custom made fyke net (Duluth Nets Inc, Duluth, MN) was set at the sampling site. The net had 15/16" mesh netting on the throat and wings and a 1.2 x 1.5 m net entrance. The two funnel throats were each equipped with 12.7 cm diameter rings to prevent turtles from entering the net, and a 1.2 m x 1.2 m x 0.76 m box sits at the upstream end of the net where captured fish are held (Figure 2.2). Small boulders were added to the holding box to provide flow refugia for captured fishes. The holding box was equipped with a zipper so that fishes could be removed during early morning and evening net checks without having to re-set the net. Wings were 1.2 m tall and equipped and with an extra lead line and 15-cm skirt to facilitate anchoring the net to the stream bottom with small boulders and rebar stakes. Sampling occurred for 1.25 to 5 days in mid to late April each year during migration peak, and the net's holding box was checked daily for captured fish; effort varied among sampling events because nets could not be operated during high flow conditions. Sicklefin Redhorse captured by the fyke net were checked for PIT tags, and untagged fish were equipped with a half-duplex (HDX) PIT tag for identification in subsequent captures. The monitoring team also sexed, measured, weighed, and checked the health and breeding conditions (i.e., whether the individual was “ripe” at time of capture) of the captured fish before releasing them upstream of the fyke net.

Beginning in 2017, a radio-frequency identification antenna sensitive to HDX PIT tags was set up in Brasstown Creek immediately downstream from the fyke net location to collect additional detections of tagged individuals during spawning and post-spawning seasons (March–July). The antenna recorded the ID of the fish when it swam over the antenna. Detections of tagged fish were collected continuously throughout the period that the antenna was implemented in the river. Data from the antenna were retrieved by downloading detections from the datalogger onto a computer at the end of the sampling period.

Statistical methods

We used a Jolly-Seber model (Jolly 1965; Seber 1965) to analyze the CMR data under a Bayesian hierarchical statistical framework to obtain parameters relevant to population dynamics of adult Sicklefin Redhorse in Brasstown Creek. We used the model to estimate annual apparent survival probability, annual recruitment, annual population size, and detection probabilities of different gear types. The annual survival probability is “apparent” because our model does not account for temporary emigration of individuals from the sampling area between sampling periods, and thus the estimates obtained are not “true” survival probabilities. Initial analyses revealed that a low recapture rate from seining resulted in biologically unreasonable estimates for population size and recruitment. The seining data set also complicated the analysis because seine captured fish were tagged with full-duplex (FDX) PIT tags which were not detectable on the PIT antenna array. Therefore, we removed captures by seine net (n = 55) from the dataset for the final analysis.

We constructed individual capture histories by denoting whether an individual was captured and by which gear it was captured in a given year. The population parameters were estimated under annual timesteps, therefore we collapsed multiple detections by the same gear type within a year into a single detection for the capture history. To estimate detection probability of individuals by different types of gear while accounting for cases where individuals were detected by more than one gear within a year, we assigned each capture event of individual *i* at time *t* to one of four total observation states, $y_{i,t}$. Each observation state is associated with a unique probability of detection, given the fish was alive and available for sampling (Table 2.2).

We modeled the capture event as a categorical outcome based on detection probability of an individual *i* at time *t* ($cap.prob_{i,t}$):

$$y_{i,t} \sim \text{Categorical}(cap.prob_{i,t})$$

In the state process of the model, the true state of the individual in the current occasion ($z_{i,t}$) depends on its true state in the previous occasion ($z_{i,t-1}$). If an individual was already alive (i.e., part of the population; $z_{i,t-1} = 1$) during the previous occasion, then it was not available for recruitment ($a_{i,t-1} = 0$) and $z_{i,t}$ is a Bernoulli outcome with survival probability from the previous time period (φ_{t-1}). If an individual is not alive in the current occasion and was available in the previous occasion ($z_{i,t}$= 0; $a_{i,t-1}$ = 1), then it is available to be recruited ($a_{i,t}$ = 1) and its state in the current occasion is a Bernoulli outcome based on entry probability γ_{t-1}:

$$z_{i,t} \sim Bern(z_{i,t-1} \times \varphi_{t-1} + a_{i,t-1} \times \gamma_{t-1})$$

Our data are limited and thus do not allow for estimating annual survival probabilities as independent parameters. Therefore, to account for temporal variation in survival probability, we used a generalized linear model to estimate a time trend in survival probability from each year (φ_t) with β_0 as the intercept, β_1 as the slope, and centered sampling year ($Year_{ctr}$) as the covariate by setting the median year (2018) as year 0, and the years before and after as years ±1-3 :

$$logit(\varphi_t) = \beta_{0\varphi} + \beta_{1\varphi} \times Year_{ctr}$$

We estimated entry probability, number of recruits, and population size by employing the data augmentation method (Kery and Schaub 2011). We added many pseudo-individuals (unknown potential members of the population with all "0" capture histories) to the pool of individuals from which fish are recruited into the adult population. The probability that an individual will enter the population each year is represented by entry probability (γ_t) which is calculated by dividing the expected number of recruits ($E(R_t)$) by the expected number of individuals available ($E(A_t)$) to be recruited in the superpopulation:

$$\gamma_t = \frac{E(R_t)}{E(A_t)}$$

where expected number of recruits varies each year with intercept β_{0r} and slope β_{1r}:

$$\log(E(R_t)) = \beta_{0r} + \beta_{1r} \times Year_{ctr}$$

The initial number (i.e., prior to 2016 when sampling began) of available individuals to be recruited ($E(A_1)$) is the same as the superpopulation size *M* (i.e., all individuals that have ever been alive in the population during the study), and in subsequent years, $E(A_t)$ is derived by subtracting number of individuals recruited to the current time period from number of available individuals in the previous time period:

$$E(A_t) = E(A_{t-1}) - E(R_t)$$

Population size at time *t* was calculated by summing the number of individuals that are alive ($z_{i,t} = 1$) during the year, and realized number of recruits at time *t* (B_t) was calculated by summing the number of individuals that were available at time *t*-1 and became part of the populations at time *t*.

We estimated detection probability of fyke nets ($pFyke_t$) over time while incorporating sampling effort (number of sampling days) in the model where μ_f is the detection probability when fyke effort is 0 and α_1 is the coefficient for effect of fyke effort on detection probability:

$$pFyke_t = \mu_f + \alpha_1 \times FykeEffort_t$$

Antenna sampling effort was standardized and then included as a covariate in the antenna detection probability model. To determine antenna effort, we first identified the core migration period for each sampling year based on detection data. We did so by quantifying number of individuals detected by the antenna every day for each year. We then used the *ssden* function within the gss package in R to fit a smoothing spline model to the resulting data. The *ssden* function provides estimated probability densities under the smoothing spline curve. We then calculated the 5% and 95% quantiles of the probability densities and removed the sampling days outside of those quantiles from the tails of the curve. The resulting range of days is considered the core migration period of Sicklefin Redhorse for each year (Figure 2.3). We then summed up the number of days that the antenna was operational (i.e., functioning without errors) within the core migration range to obtain sampling effort (Table 2.3). To evaluate the influence of PIT antenna data on parameter estimates, we ran the same model with only fyke capture data collected from 2016 to 2021 and compared the results with those from analyzing both antenna and fyke net data.

All analyses were conducted in programs R (R Core Team 2020) and JAGS (Plummer 2003) using R package "jagsUI" (Kellner 2019). JAGS (Just Another Gibbs Sampler) is a Bayesian statistical software that uses Markov Chain Monte Carlo (MCMC) samplers to generate posterior samples for each estimated parameter based on prior information and data. We assigned uninformed priors for the parameters. For parameters confined between 0 and 1, we used uniform distribution with range 0 to 1 as priors. For intercepts and slopes of generalized linear models within the hierarchical model, we used normal distribution with mean of 0 and precision of 0.01 as priors. We decided that model convergence was reached when the trace plots of MCMC chains for all parameters showed appropriate mixing as well as when the Gelman-Rubin statistics were <1.1 (Gelman and Rubin 1992). When analyzing both fyke and antenna data, we ran the model with three MCMC chains for 50,000 iterations in each chain, discarding the first

5,000 iterations as burn-in. When analyzing fyke data alone, we ran the model for 100,000 iterations, discarding the first 50,000 iterations as burn-in.

Results

A total of 276 individuals were included in the analysis. The number of individuals detected each year ranged from 63 in 2016 to 155 in 2018. The number of individuals captured by fyke net each year ranged from 14 to 106, and the number of individuals detected by PIT antenna ranged from 44 to 129 (Table 2.3). The total length of fish captured during the study ranged from 412 mm to 581 mm, while the weight ranged from 585 g to 2130 g. Across years, the fyke net sampling effort ranged from 1.25 to 5 days, and the antenna sampling effort ranged between 32 and 59.75 days.

When both fyke and antenna data were included in the analysis, the estimated apparent survival probability of adult Sicklefin Redhorse ranged between 0.85 (95% BCI = 0.78–0.91) in 2016 to 0.64 (95% BCI = 0.54–0.75) in 2020 (Figure 2.4). Population size in 2016 was estimated to be 225 individuals (95% BCI = 194–258) and decreased over time to 122 (95% BCI = 104–145) in 2021 (Figure 2.5). The expected number of recruits increased from 27 individuals (95% BCI = 10–47) in 2017 to 54 individuals (95% BCI = 36–76) in 2021. The realized recruits each year ranged from 14 individuals (95% BCI = 3–29) in 2017 to 36 individuals (95% BCI = 26–47) in 2021 (Figure 2.6).

Overall, estimates of population parameters were less precise when only fyke data were included in the analysis. The apparent survival probability of Sicklefin Redhorse from the fyke data only analysis showed an increasing trend, starting from 0.73 (95% BCI = 0.52–0.89) in

2016 and increased to 0.87 (BCI = 0.68–0.98) in 2020 (Figure 2.4). Population size started at 1,328 individuals (95% BCI = 848–1900) in 2016 then declined to 601 individuals (95% BCI = 362–880) in 2021 (Figure 2.5). Number of realized recruits each year ranged between 21 individuals (95% BCI = 0–81) in 2019 and 78 individuals (95% BCI = 0–418) in 2017 (Figure 2.6).

The core spring migration period for Sicklefin Redhorse in Brasstown Creek varied from year to year (Table 2.4). The start of core migration period ranged between late-March and early-April, and the end of core migration period ranged between early-May and early-June. Detection probability by fyke nets was lower compared to that of PIT antenna in most years (Figures 2.7–2.8). The evidence suggests number of sampling days had a positive effect on fyke detection probability (α_f = 0.61, 95% BCI = 0.46–0.76) based on the analysis with both antenna and fyke data. Based on model predictions, as effort (number of sampling days) increases, detection probability by fyke net also increases (Figure 2.9). In contrast, number of sampling days does not have a significant effect on antenna detection probability (α_P = -0.21, 95% BCI = -0.60–0.18; Figure 2.10).

Discussion

Sicklefin Redhorse is a rare endemic fish in a region experiencing increasing anthropogenic disturbances. Conservation of the species would be best aided by an effective monitoring program and a better understanding of their population status. Our study demonstrated that including detection data from a PIT antenna in the analysis produced different results for estimates of most model parameters which could have important implications for management of Sicklefin Redhorse populations in the Hiawassee River Basin. Foremost, estimates of adult population size in Brasstown Creek in GA were almost an order of magnitude lower and much more precise when utilizing both fyke and antenna data in the analysis compared to fyke net data alone. In addition, population size and apparent survival probabilities appear to decline over the study period in the combined model. However, when only fyke data are included, survival probability shows an increasing trend over time (Figure 2.4). Overall, detection probability by fyke net was lower compared to that of PIT antenna, indicating antennas may be a more efficient population monitoring tool.

From the management standpoint, the difference between population sizes estimated using the two datasets could lead to different management approaches. One of the potential conservation actions in the Sicklefin Redhorse CCA is to stock young fish in Georgia waters "if determined to be appropriate" (U.S. Fish and Wildlife Service 2015). Relying solely on fyke net data could potentially lead to an overestimation of population size and lead biologists to decide that stocking is not needed which may not be the appropriate strategy. We emphasize that the model population estimates based on combined data sources did not fall within the 95% credible intervals of the fyke net model estimates. If we had only utilized fyke net data for our analysis, we may have been unconcerned about population status because estimates always exceed or overlapped 500 individuals, a common benchmark for demographic viability used in conservation biology (Jamieson and Allendorf 2012).

Some of the estimated population parameters and detection probabilities corroborate with those from similar studies. For example, the estimated apparent survival probabilities of Sicklefin Redhorse from both the fyke net and combined datasets are similar to that of other long-lived Catostomids (Jennings et al. 2000; Young and Koops 2014; Scoppettone et al. 2015). Further, antenna detection probability estimated from our model remained around 0.5 throughout the study which is comparable to estimates from other studies. For example, Pearson et al. (2016) found a similar detection probability for PIT antenna (0.42) used in their study monitoring Humpback Chub (*Gila cypha*) in the Little Colorado River, Colorado. Additionally, Adams et al. (2006) tested efficacy of PIT antenna at detecting juvenile Chinook Salmon in a study pond and found an average detection probability over 27 weeks to be over 0.4.

Interestingly, estimated fyke detection probabilities are lower when we analyzed only fyke data compared to combined data. We suspect that the lower detection probabilities for the fyke-only analysis correspond to that model estimating an increasing survival and much larger population size such that the recaptures in the fyke net would be considered small relative to the overall population size. By adding the antenna data, no new marks are generated but "new" recaptures are seen beyond those that appear in the fyke recaptures alone. In general, these additional recaptures, given the same number of marks, would lead to lower estimates of abundance, which could lead to the increase in fyke detection probability in the combined analysis.

When designing a population monitoring program, biologists would achieve more precise results if they weigh advantages and challenges of various monitoring methods. Physical capture methods such as fyke nets afford biologists the opportunity to capture unmarked fish and tag them so they can be identified in subsequent captures. Additionally, with the fish in hand, biologists can examine the condition of the fish and record data such as length and weight that are not available for antenna detections. However, the efficiency of physical capture methods can be affected by several factors. For example, a common environmental cue triggering migration of freshwater fishes is water temperature. Sicklefin Redhorse start spring migration when water temperature reaches 10 °C – 16 °C (Favrot and Kwak 2018). Favort and Kwak (2018) observed an abrupt halt in migration in fish equipped with radio transmitters when a cold front led to a drop in water temperature in Hiwassee River. A similar phenomenon was observed in our study: when water temperature dropped due to a cold front in spring of 2021, fish captured by fyke nets also decreased substantially from 41 captures before and three captures after the temperature drop (B. Albanese, Georgia Department of Natural Resources, personal communication). Additionally, the success of fyke nets is highly dependent on available personnel as well as sampling conditions (i.e., weather and water level), limiting opportunities for sampling.

Our study presents evidence supporting the utility and efficacy of using PIT antennas to collect additional detections of marked animals when monitoring a population. Other studies examining effectiveness of PIT antennas also demonstrated that detection probability of fish improved, and uncertainty of population parameter estimates decreased when antennas were used in combination with other sampling methods to collect mark-recapture data (Hewitt et al. 2010; Dzul et al. 2021b). The additional detections of marked fish from PIT antenna in our study resulted in more precise estimates for population parameters. The 95% BCI for survival probability, number of recruits, and population abundance are all narrower when antenna data were included in the analysis compared to analysis with fyke data only, indicating reduced uncertainty surrounding these parameters (Figures 2.4–2.6). Further, using PIT antennas to detect marked fish remotely is a less invasive approach that allow biologists to collect data without re-disturbing the animals than traditional sampling methods involving physical recaptures.

Additionally, physical capture methods such as fyke or seine nets could be labor-intensive. PIT antennas, on the other hand, can be set up in the sampling area for extended periods of time to collect data without much ongoing labor investment.

Perhaps the biggest drawback of PIT antennas is that they can only detect tagged fish, and thus cannot be used as the sole method of data collection (Dzul et al. 2021b). Researchers who wish to take advantage of the detection efficiency of PIT antennas will need to combine it with a physical capture method that will allow for tagging fish for identification. Further, the efficacy of PIT antennas could be affected by factors such as how the antennas are set up, the position of fish when they pass the antennas, and environmental factors. Zentner et al. (2021) reviewed studies using mobile PIT antennas and antenna arrays and discovered that common factors that affected detection efficiency of the gears included tag size, tag orientation, amount of water discharge, and water turbidity. Similar factors may also affect detection efficiency of stationary passive PIT antenna arrays. For example, increases in discharge may allow fishes to swim over the antenna without detection when water depth exceeds antenna detection distance. The efficiency of the multiplex PIT system in a river was lower during stormy days compared to normal days (Aymes and Rives 2009). Storms could lead to flooding, damaging the antennas and their components (batteries, reader, tuning capacitor) which can unknowingly malfunction and leave gaps in sampling periods (B. Albanese, Georgia Department of Natural Resources, personal communication). The initial cost of PIT tags and antennas is also higher compared to other sampling methods. However, by conducting a cost-benefit analysis comparing using PIT antennas and seine nets Barbour et al. (2012) found antennas to be more cost-effective and worth the expense.

Our model does not account for permanent or temporary emigration of fish from the sampling area, which could skew estimates of apparent survival probability and abundance (Horton et al. 2011; Dzul et al. 2021a). Although Sicklefin Redhorse exhibits high between-year site fidelity to spawning grounds (Favrot and Kwak 2018), we observed at least one fish that was captured in Brasstown Creek but was later detected in Valley River, NC (B. Albanese, GA Department of Natural Resources, unpublished data). Further, individuals of some sucker species have been observed to skip spawning during years with suboptimal spawning conditions (Burdick et al. 2015). If such behavior exists in Sicklefin Redhorse, it could render a portion of the adult population unobservable at spawning grounds during certain years. Additionally, our data does not include fish that spawn in the lower portion of Brasstown Creek. Future studies that incorporate spatial heterogeneity into models will help better quantify population dynamics of fish populations (Raabe et al. 2014; Dzul et al. 2018). Lastly, our analysis does not distinguish survival probabilities between males and females. Future iterations of the model could incorporate sex-specific survival probabilities to examine whether they differ and thus better inform management decisions.

The results from this study will help guide management decisions of Sicklefin Redhorse populations from the SRCC. For example, a potential management action that has been discussed is to translocate adult Sicklefin Redhorse from Brasstown Creek, GA to other locations to establish new populations within the species' historic range (B. Albanese, Georgia Department of Natural Resources, personal communication). The feasibility of the management action depends on the current status of the Sicklefin Redhorse population in Brasstown Creek informed by our analysis.

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Table 2.1. Gears used to capture/detect Sicklefin Redhorse during each sampling year from 2014 to 2018. "+" indicates the gear was used during that year.

Gear used	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Seine	+	+	+					
Fyke net			+	+	+	+	+	+
PIT antenna				+	+	+	+	+

Table 2.2. Possible observation states and associated detection probability for individual Sicklefin Redhorse alive and present in the sampled population during each year (*t*) from 2016 to 2021. *pFyke* indicates detection probability by fyke net, and *pPIT* indicates detection probability by antenna.

Observation state ($y_{i,t}$)	**Detection probability (*$cap.prob_{i,t}$*)**
Not detected	$(1 - pFyke_t) \times (1 - pPIT_t)$
Detected in fyke only	$(1 - pPIT_t) \times pFyke_t$
Detected by antenna only	$(1 - pFyke_t) \times pPIT_t$
Detected by fyke and antenna	$pFyke_t \times pPIT_t$

Table 2.3. Number of unique individual fish detected each year and sampling effort (days) by each gear type in Brasstown Creek, GA. The PIT antenna was not in operation in 2016. Some fish were detected by both fyke net and PIT antenna.

Year	Fyke net captures	Fyke effort	PIT antenna detections	Antenna effort
2016	63	3.00	NA	NA
2017	106	5.00	111	32.00
2018	48	4.00	129	57.75
2019	25	3.00	73	34.50
2020	14	1.25	75	56.00
2021	44	3.75	44	59.75

Table 2.4. Start and end dates of core migration periods of Sicklefin Redhorse population in Brasstown Creek, GA based on antenna detections of adult Sicklefin Redhorse with PIT tags.

Year	**Start of core migration**	**End of core migration**
2017	April 3	May 4
2018	March 26	May 22
2019	March 30	May 7
2020	March 25	May 19
2021	April 7	June 5

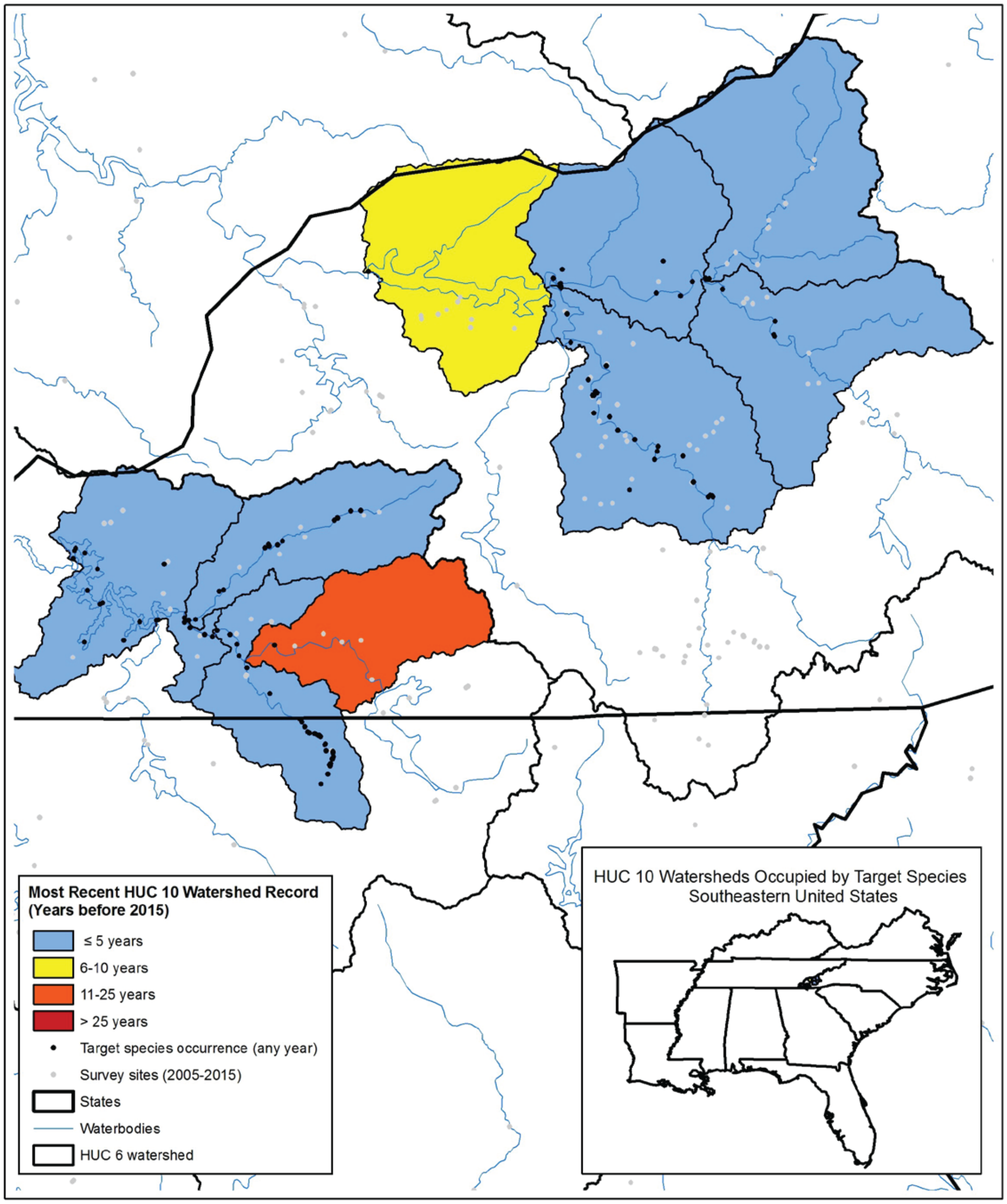

Figure 2.1. Current (2022) range of Sicklefin Redhorse (*Moxostoma sp.*) in the U.S. Map produced by Georgia Department of Natural Resources and Tennessee Aquarium Conservation Institute.

Figure 2.2. Fyke net set in Brasstown Creek in April 2017. Photo by Tom Martin, Western Carolina University, used with permission.

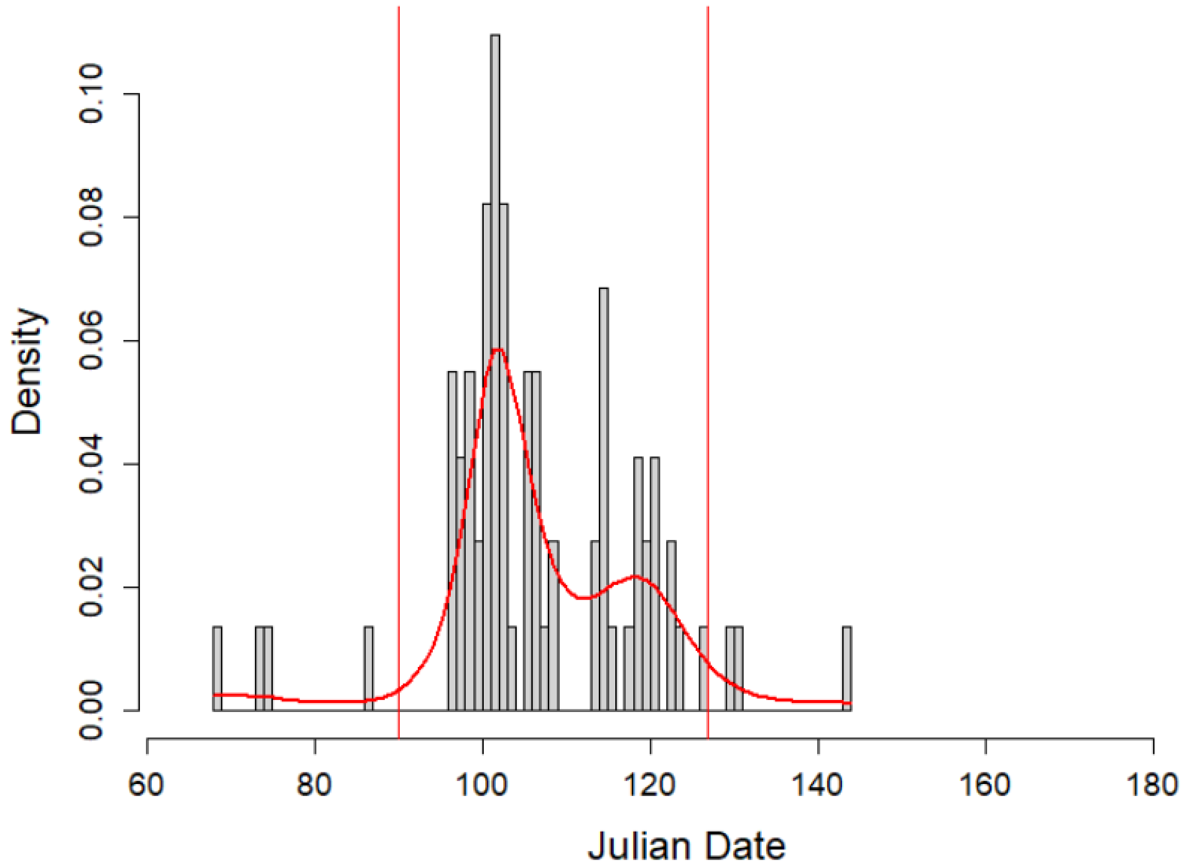

Figure 2.3. Density plot of antenna detection data from Brasstown Creek in 2019. Histogram represents a summary of number of individuals detected by antenna on a given day. Thick red line represents probability density curve fitted to the data. Vertical red lines represent 5% and 95% quantiles of the estimated probability densities based on detection data. Range of dates between the two vertical lines represents core spawning migration period for Sicklefin Redhorse in 2019.

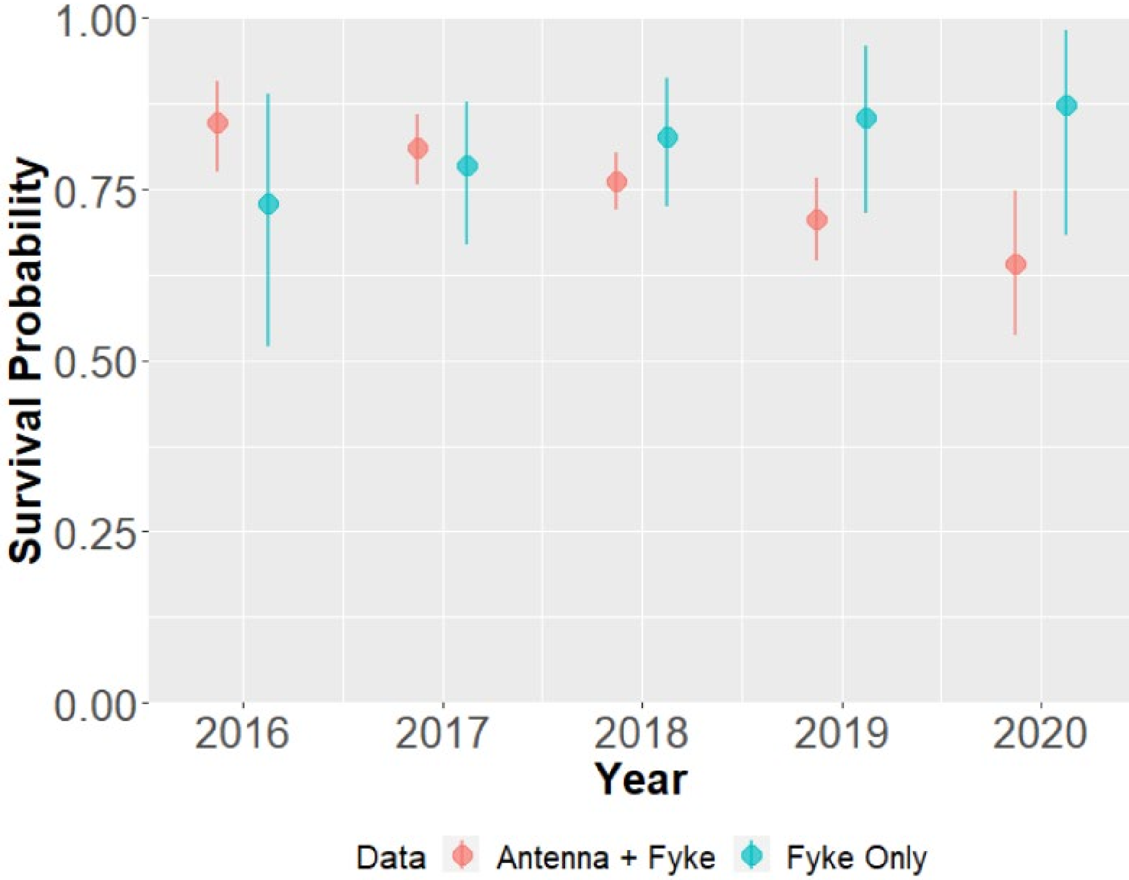

Figure 2.4. Estimates of apparent survival probabilities of the spawning Sicklefin Redhorse population in 2016–2020 in Brasstown Creek, GA. Colored dots indicate the mean of posterior MCMC samples from the Bayesian Jolly-Seber model with different datasets. Vertical lines indicate the 95% Bayesian credible intervals of the estimates.

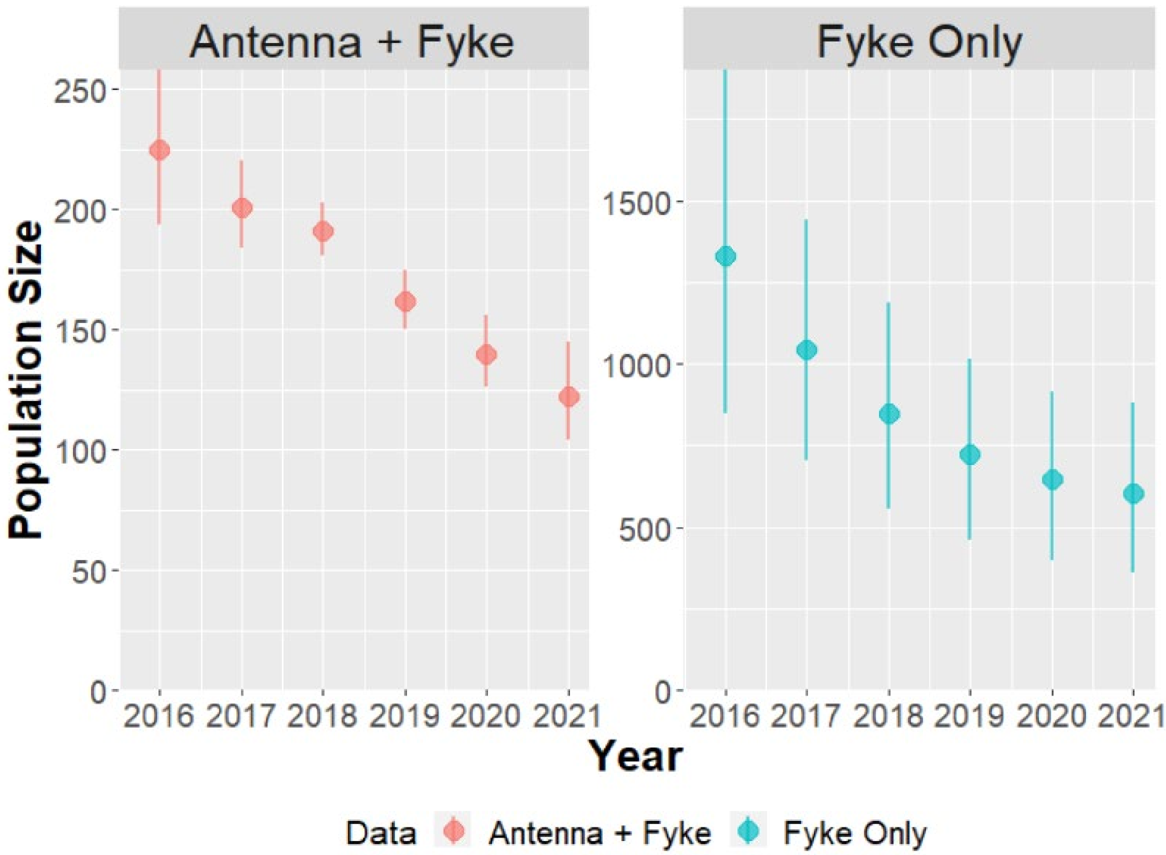

Figure 2.5. Estimated population sizes of Sicklefin Redhorse spawning population in 2016–2021 in Brasstown Creek, GA from analyzing different datasets. Colored dots indicate means of posterior MCMC samples from the Bayesian Jolly-Seber model. Vertical lines indicate the 95% Bayesian credible intervals of the estimates. Note difference in Y-axis range between plots.

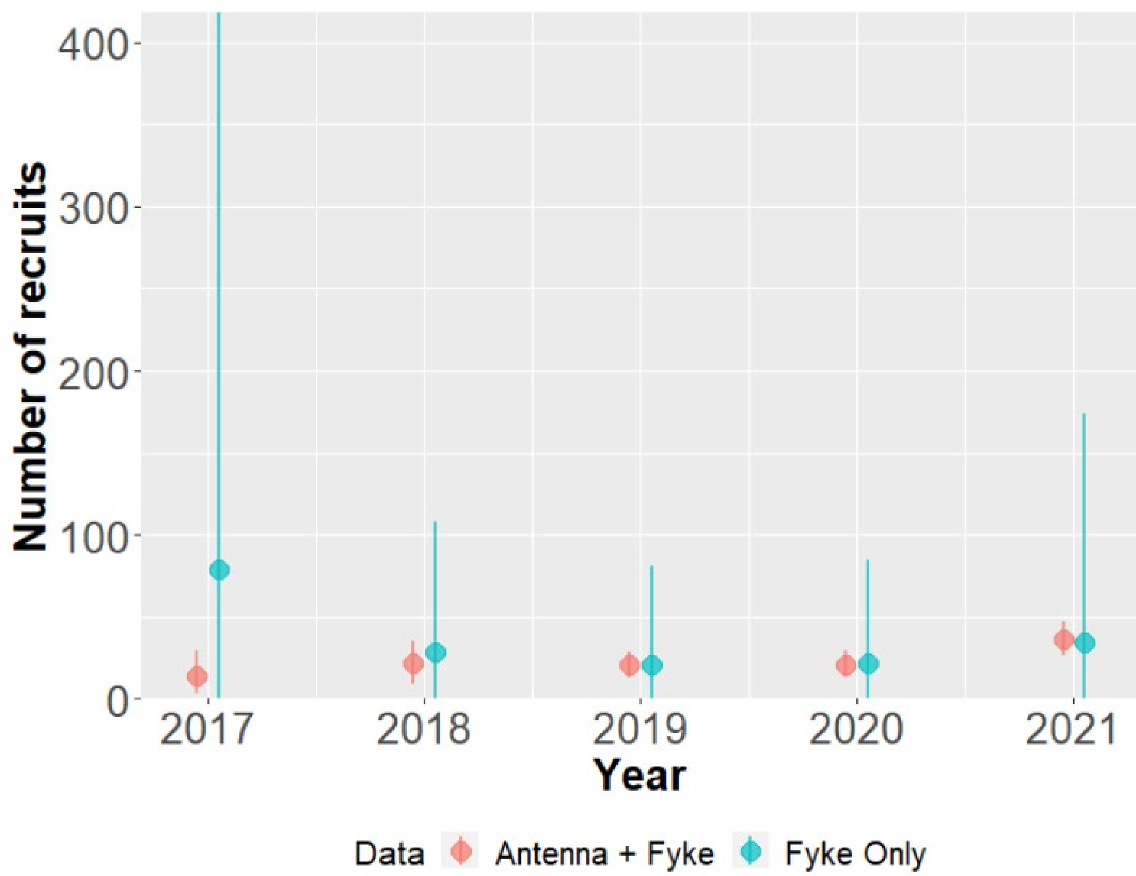

Figure 2.6. Estimated realized number of adult Sicklefin Redhorse recruited into the spawning population in 2017–2021 in Brasstown Creek, GA. Colored dots indicate the mean of posterior MCMC samples from the Bayesian Jolly-Seber model with different datasets. Vertical lines indicate the 95% Bayesian credible intervals of the estimates.

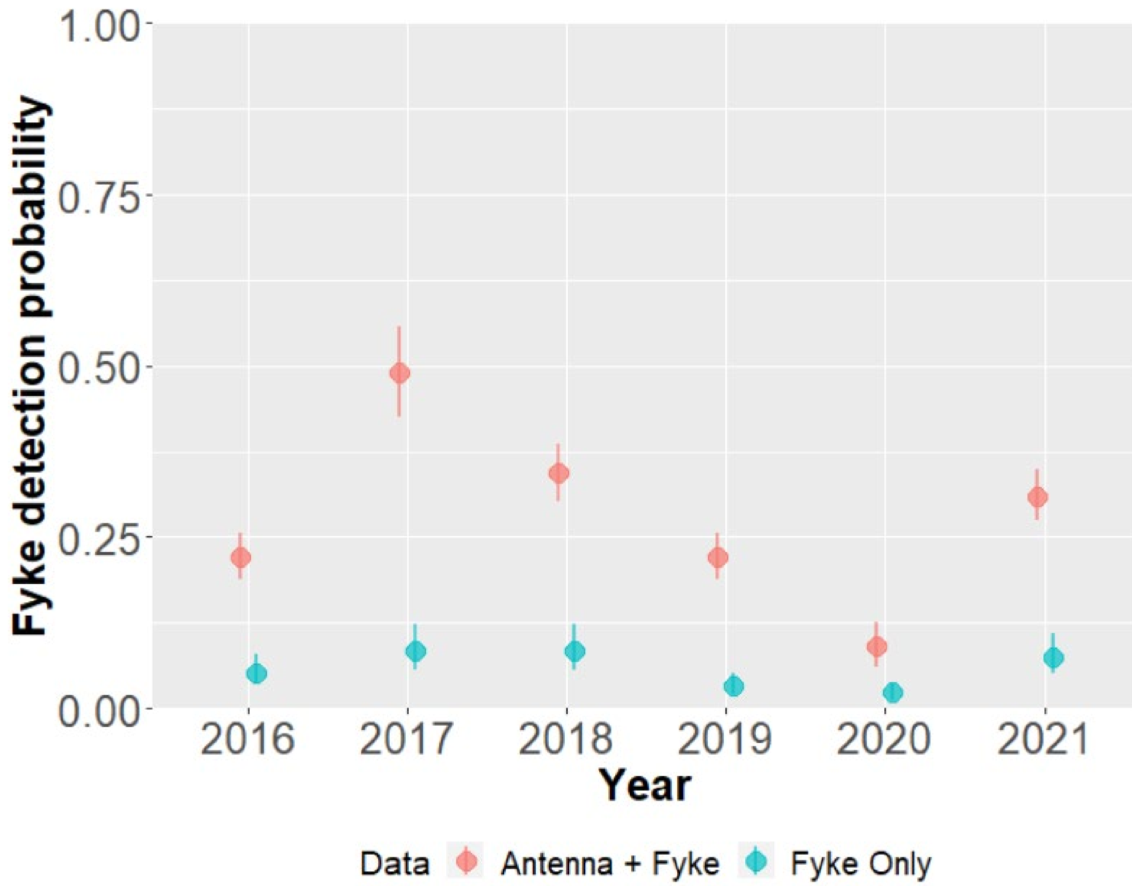

Figure 2.7. Detection probability estimates of fyke net during 2016–2021. Colored dots indicate the mean of posterior MCMC samples from the Bayesian Jolly-Seber model with different datasets. Vertical lines indicate the 95% Bayesian credible intervals of the estimates.

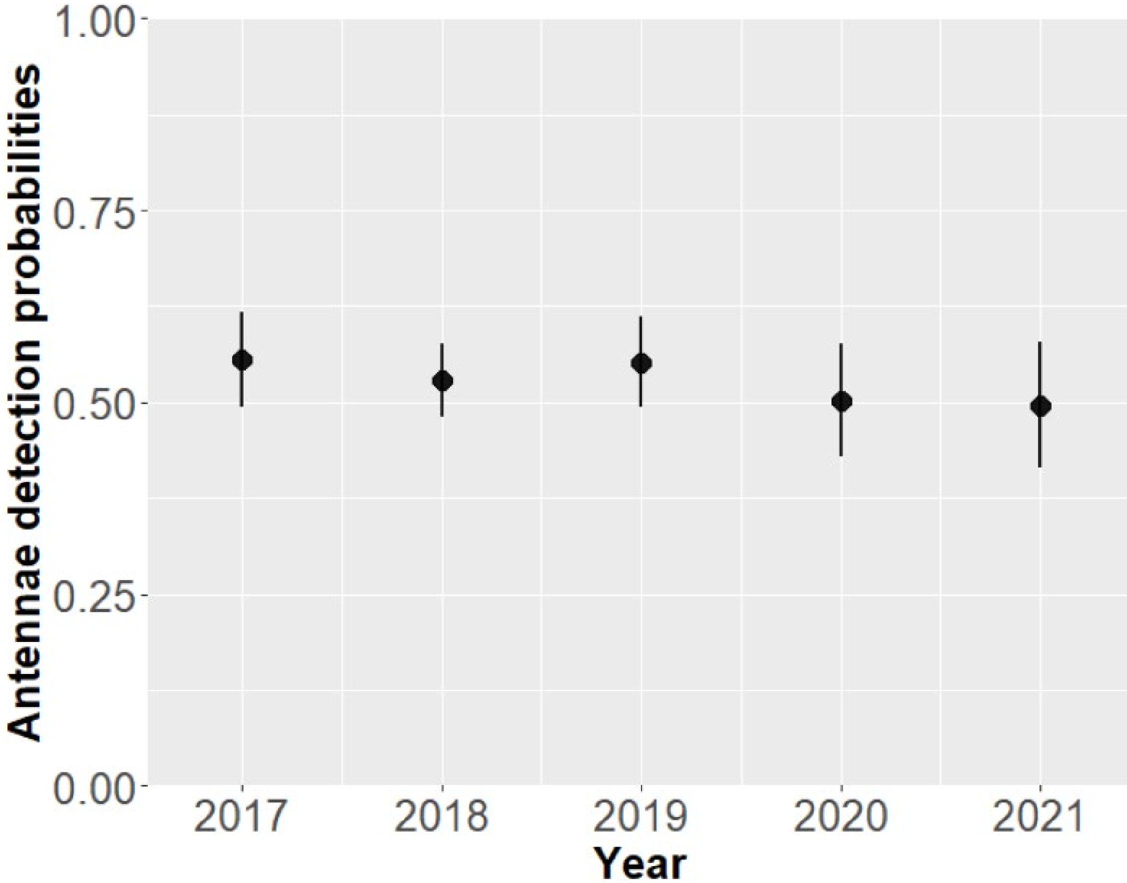

Figure 2.8. Estimates of PIT antenna detection probabilities during 2017–2021. Black dots indicate the mean of posterior MCMC samples from the Bayesian Jolly-Seber model from analysis of dataset with both fyke and antenna detections. Vertical lines indicate the 95% Bayesian credible intervals of the estimates.

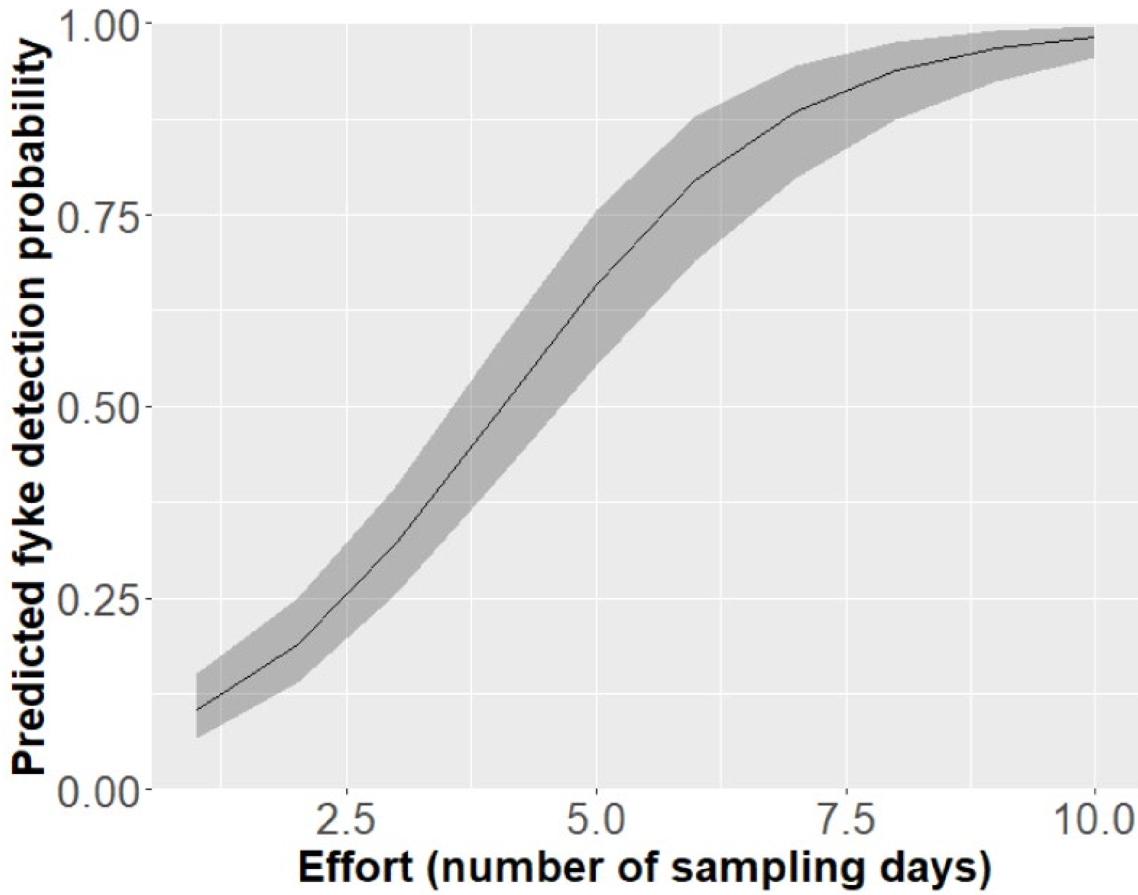

Figure 2.9. Predicted detection probability of Sicklefin Redhorse by fyke net based on number of sampling days that fyke nets are operated.

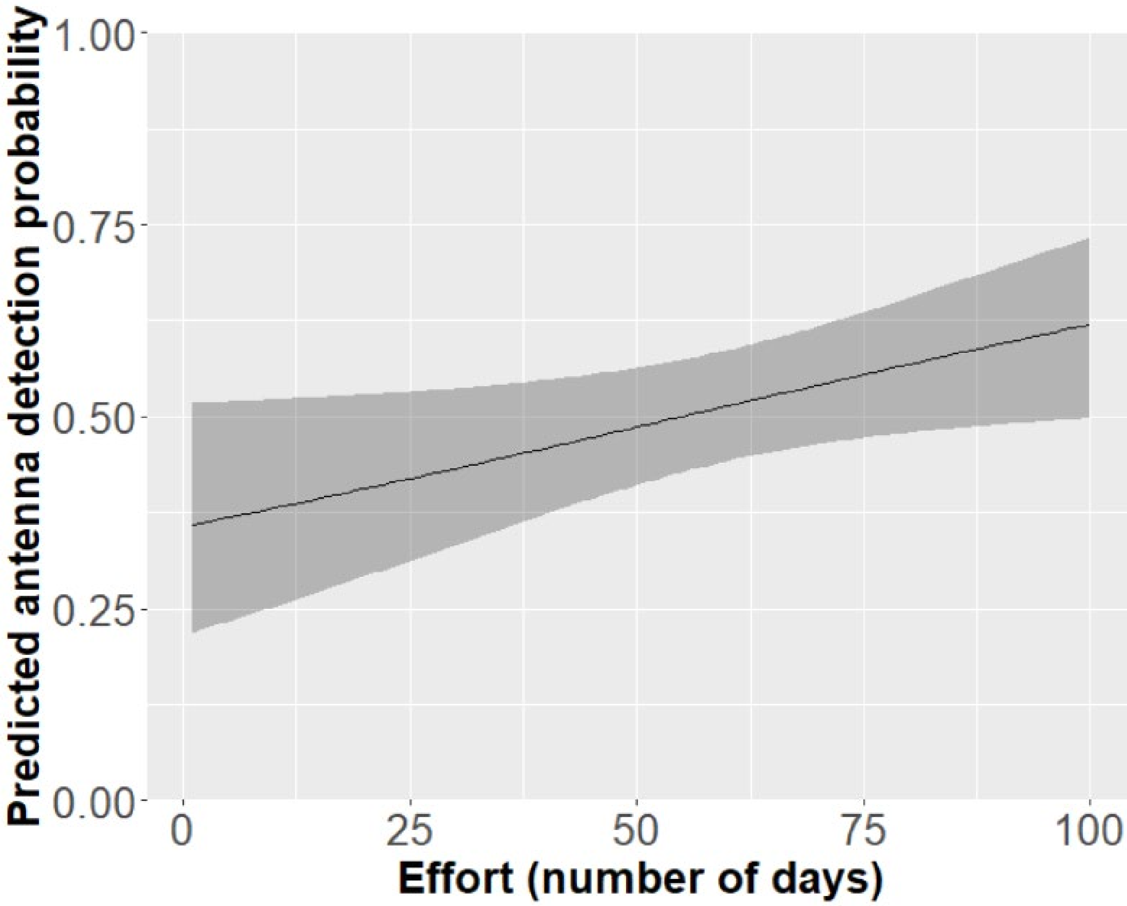

Figure 2.10. Model-predicted antenna detection probability based on the number of sampling days within the core migration period. Black line indicates the mean of posterior samples, and shaded area indicates 95% Bayesian credible intervals for the predictions.

CHAPTER 3

APPLYING STRUCTURED DECISION MAKING TO CONSERVATION OF AN IMPERILED FRESHWATER FISH[2]

[2]Hsiung, A. C., Jennings, C. A., Moore, C. T., and B. Irwin. To be submitted to *Biological Conservation*

Abstract

Structured decision-making (SDM) has gained popularity in natural resource management as a process to guide stakeholders through evaluation of potential management strategies. Benefits of SDM include clarifying the management problem, making stakeholder values explicit, and incorporating uncertainty surrounding system responses to implementation of management actions. When deployed under an adaptive management (AM) design, SDM offers a way for natural resource managers to learn about the managed system through action implementation and monitoring the system's response to reduce uncertainty. In this study, we guided stakeholders through the SDM process to evaluate potential management strategies to conserve Robust Redhorse (*Moxostoma robustum*), an imperiled freshwater fish on the Atlantic slope of the southeastern U.S. The stakeholders identified objectives related to adult abundance and overall population persistence, and they specified potential management actions, including stocking young-of-the-year (age-0) fish and improving spawning and rearing habitats. We used available sampling data to construct a multistate mark-recapture model to estimate size stage-specific survival and transition probabilities of Robust Redhorse within basins. We then used a stage-based population viability analysis (PVA) to simulate population trajectories and evaluate probability of meeting management objectives under alternative decision scenarios. We found that, in some cases, scenarios that did not result in improved age-0 fish recruitment and survival probabilities were less likely to result in viable populations. This SDM process supports recovery efforts for Robust Redhorse and provides a framework for adaptive management of the species in the future.

Keywords: *decision analysis, Catostomidae, Robust Redhorse, southeastern U.S., population estimation, population projection*

Introduction

Conservation of natural resources often involves making decisions about implementation of conservation or management actions at a given time. By definition, a decision is a choice between alternative options to meet objective(s) (Fuller et al. 2020; Hemming et al. 2022). Fuller et al. (2020) stated that natural resource "management simply cannot occur in the absence of decision making at any levels". Natural resource managers today often need to make decisions under complex contexts where multiple, sometimes competing, objectives and diverse values are involved (McGowan et al. 2014; Converse and Grant 2019). Under such contexts, effective and transparent decision making is especially important to take advantage of limited resources and account for diverse points of view from stakeholders (Keeney 1996; Fuller et al. 2020). A decision-making process that embodies these qualities is more likely to lead to a defensible decision and increase stakeholder buy-in even in the face of uncertainty and unexpected outcomes (Fuller et al. 2020; Smith et al. 2020; Hemming et al. 2022).

Structured decision making (SDM) is a process for natural-resource managers to evaluate potential management strategies based on predicted capacity to achieve management objectives. Importantly, SDM incorporates stakeholder values into the decision-making process, promoting transparency about how decisions are made (Gregory and Long 2009; Brignon et al. 2019; McMurdo Hamilton et al. 2021). The SDM process has been widely applied in natural-resources management and biodiversity conservation (Irwin et al. 2011; Maestri et al. 2017; O'Donnell et al. 2017; Robinson et al. 2017). SDM provides a framework that allows stakeholders to follow a series of steps when making decisions. These steps include: 1) framing the management/ecological problem and characterizing the full decision context, 2) specifying management objectives, 3) developing alternative management strategies, 4) evaluating consequences of each management strategy 5) identify preferred alternative, and 6) implement action (Runge et al. 2013; Figure 3.1).

Adaptive management is a form of SDM applicable to recurrent decision making that attempts to reduce uncertainty at each decision and applies the increased learning to future decisions (Holling 1978; McFadden et al. 2011). Uncertainty is reduced by monitoring responses to implemented management actions in achieving management objectives while focusing on alternatives that will lead to learning opportunities (Holling 1978; Milner-Gulland et al. 2010; Rist et al. 2012; Canessa et al. 2016). For instance, the additional knowledge gained from monitoring a species response after a management action is implemented would be used to reduce a decision-relevant uncertainty prior to the choice of the next management action. Adaptive management has been applied to the management of commercial and game species (Johnson 2011; McGowan et al. 2015; Decalesta 2017), pest species (Jones et al. 2015), and threatened and endangered species (Runge 2011; Tyre et al. 2011; McGowan et al. 2015).

Evaluating management strategies for fish and wildlife species often involves forecasting future population states under different management scenarios and assessing expected population status after a set time period. Researchers have used population viability analysis (PVA), a modeling framework that simulates the future dynamics of a population, to predict species' response to environmental changes and management action (Legault 2005; McGowan et al. 2017; Milligan et al. 2018; Howell et al. 2020; Neville et al. 2020). Additionally, PVA models can consider uncertainty associated with population parameters and a species' or population's response to conservation and management actions, allowing natural-resource managers to visualize how uncertainties affect management outcomes.

Study species

Robust Redhorse (*Moxostoma robustum*) is an imperiled freshwater fish found in large Atlantic slope rivers in Georgia, North Carolina, and South Carolina (Figure 3.2). The species was originally described by Edward Drinker Cope (1870) but was considered “lost” to science until some specimens collected from the Savannah River GA/SC in the late 1980s from the Oconee River in Georgia in the early 1990s were identified as Robust Redhorse. Robust Redhorse is a heavy-bodied potamodromous (i.e., seasonal migration occurs solely in freshwater) species with rose-colored fins and can be distinguished from other species of redhorse by their uniquely shaped plicate lips. They inhabit medium to large rivers and feed primarily on bivalves and occasionally aquatic invertebrates (Fisk et al. 2013). Adult Robust Redhorse aggregate at gravel bars upstream during the spawning season (April–June) then migrate downstream to non-spawning habitats with deeper water (Grabowski and Isely 2006). After eggs hatch, larvae spend about 2 – 4 weeks in the interstitial spaces in the gravel before emerging into the water column (Jennings et al. 2010).

Some populations of Robust Redhorse have been declining or remaining at low abundance for the last two decades (Robust Redhorse Conservation Committee 2014). Currently, the species is a candidate for listing under the Endangered Species Act (1973). In 2002, a Candidate Conservation Agreement with Assurances was established between Georgia Power Company, Georgia Department of Natural Resources, and U.S. Fish and Wildlife Service to implement conservation actions to restore Robust Redhorse population in the Ocmulgee River in GA (U.S. Fish and Wildlife Service 2002). Several threats potentially contributed to the decline or suppress the recovery of Robust Redhorse. Migration routes (especially upstream) of many riverine fishes in North America have been obstructed by dams (Schilt 2007). There are several dams present within the Robust Redhorse range, which could potentially block migratory routes between spawning and non-spawning grounds and limit recruitment (Grabowski and Isely 2006). Fine sediments accumulating in spawning and rearing habitats can also affect recruitment of young-of-the-year into the population by filling the interstitial spaces between gravel substrate into which adults lay eggs, thus reducing larvae survival to emergence (Jennings et al. 2010) Additionally, larvae that emerged from substrate with more fine sediments are smaller compared to those emerging from substrate with less or no fine sediments (Jennings et al. 2010). Water flow, specifically amount and timing of water availability, is another important factor affecting rearing habitat for Robust Redhorse. In experiments altering flow velocity, Robust Redhorse larvae exposed to pulsed, high-velocity water flow grew more slowly and had lower survival rate compared to fish that did not experience such flows (Ruetz III and Jennings 2000; Weyers et al. 2003). Insufficient water in the spawning and rearing habitats could also result in dewatering of redds produced by spawning Robust Redhorse in the river (Fisk et al. 2013). As with other long-lived sucker species, adult Robust Redhorse have relatively high survival rate (Jennings et al. 2000). However, anecdotal accounts suggest that incidental mortality by bowfishing could negatively impact adult survival, as Robust Redhorse co-occur with similar-appearing carp and non-threatened sucker species (C. Straight, U.S. Fish and Wildlife Service, personal communication).

The Robust Redhorse Conservation Committee (RRCC) was formed in 1995 shortly after the rediscovery of the Robust Redhorse population in the Oconee River, GA. Established under a Memorandum of Understanding, the RRCC is a partnership among stakeholders from federal and state natural resource agencies, academic institutions, utilities, and non-profit organizations with the purpose of restoring the species and its populations within its historical range. Members of the RRCC have been engaging in monitoring and management of Robust Redhorse populations range wide for nearly three decades.

The overarching goal of this study was to use principles of SDM to help the RRCC build a framework for adaptive management. The two main objectives related to the project goal were: 1) construct a population model to estimate size stage-specific parameters for Robust Redhorse populations, and 2) conduct a PVA to project Robust Redhorse populations under various scenarios to help stakeholders evaluate potential management actions. The outcomes of the SDM process could potentially be included in the eventual Species Status Assessment (U.S. Fish and Wildlife Service 2016) for Robust Redhorse to inform listing decisions for the species and help stakeholders pursue adaptive management to conserve and manage the species for the future.

Methods

Structured decision-making process

We held several interactive workshops of varied lengths (2-6 hrs) with RRCC members between September 2017 and March 2020. Some workshops were held during RRCC's annual meetings where stakeholders gathered and presented annual updates of research and monitoring activities, as well as discuss issues and future plans associated with recovery activities. Some later workshops were held with separate technical working groups in charge of monitoring and managing Robust Redhorse populations within a specific watershed.

Prior to the 2018 RRCC annual meeting, we prepared a problem statement which describes the context of the decision based on information gained from previous discussions with RRCC members. The statement was presented to the members of RRCC at the meeting, and the members provided feedback on statement content and semantics. Changes were made based on the feedback at the RRCC meeting in September 2018, and the updated statement is as follows:

"*The Robust Redhorse (*Moxostoma robustum*) is a freshwater fish species in medium to large rivers on the Atlantic slope in the southeastern U.S. The species has been extirpated and reduced from parts of its native range. Soon after its rediscovery, a coordinated effort was initiated under a Memorandum of Understanding to monitor and manage the species within its range. The resulting Robust Redhorse Conservation Committee (RRCC)[1] includes federal and state agencies, industry representatives, and members of academia, who are collaborating to consider a range of management actions, including augmenting the populations and providing habitat protection/restoration to restore the populations within the species historical range in Georgia, South Carolina, and North Carolina[2] for the next 100 years. The management decisions will be made through an iterative process annually, and newly developed information will help future decision making through an adaptive management framework.*

[1]Georgia Department of Natural Resources, South Carolina Department of Natural Resources, North Carolina Wildlife Resources Commission. Georgia Power Company, Duke Power Company, South Carolina Electric and Gas Company, Georgia Wildlife Federation, U.S. Geological Survey, USDA Forest Service, and U.S. Fish and Wildlife Service.

[2]Extracted from Robust Redhorse Conservation Committee Policies (2002)"

The problem statement includes some essential components, such as the motivation behind the decision, who the decision makers are, how often the decisions will be made, potential management actions, and the temporal and spatial scale for evaluating management strategies (Converse and Grant 2019, Smith et al. 2020, Hemming et al. 2021). The timeframe of 100 years was informed by generation time of the species. Forecasting populations for multiple generations into the future is common practice (USFWS Species Status Assessment Framework 2016). The oldest estimated age ever recorded for Robust Redhorse is 27 years old; therefore, the Committee considered 100 years to be the appropriate timeframe to project population trends.

The existing Robust Redhorse populations are managed as five distinct units: Altamaha, Broad (GA), Savannah, Pee Dee, and Santee. A management unit contains populations from one to three river basins, and these units differ due to variations in population genetics, river conditions, land uses, and management history. During the workshops, the group decided that they wanted to focus the management scenario evaluation on Altamaha, Broad (GA), Savannah, and Pee Dee management units. During the management objectives discussion, RRCC members agreed on the fundamental objective – to restore and maintain Robust Redhorse populations within its historic range, and the means objectives: 1) stable or increasing population size, 2) population persistence, 3) self-sustaining population, and 4) maintain adaptive potential. In addition to management objectives, we also solicited performance metrics and reference points that will be used to evaluate management actions for their capacity to meet management objectives for each management unit (Bunnefeld et al. 2011; Irwin et al. 2011; Table 3.1, Appendix A).

Subsequent workshops were held separately with working groups in charge of managing each unit. From December 2019 to March 2020, we met with the working groups to solicit potential management actions, as well as potential consequences of implementing the management actions on the populations. During these workshops with the RRCC, we also discussed the potential structure of population-dynamics models that could be used to estimate unknowns based upon currently available data or for scenario forecasting to make predictions based on the specified available management actions. The management scenarios for each unit will be described following the description of the population estimation and PVA models.

Population dynamics model

The RRCC has been monitoring extant Robust Redhorse populations since the early 1990's. We obtained capture-mark-recapture data from RRCC for the Pee Dee and Savannah management units because these datasets were most complete in terms of temporal coverage as well as availability of mark-recapture records for the individuals within the populations. Electrofishing methods were used for most of the sampling, which occurred during the spawning season (April–June) at spawning shoals where Robust Redhorse gather. Additional data were also included when Robust Redhorse were captured during standardized sampling for other species by cooperating agencies.

We constructed a multistate mark-recapture model to estimate survival, transition, and detection probabilities of Robust Redhorse populations with year as the time step (Kery and Schaub 2011). We used a multistate model because age information was lacking for most of the captures of Robust Redhorse and management actions that are considered by the stakeholders are more likely to affect populations at the resolution of life stage rather than age. Thus, our multistate estimation model includes three states of life stage. We used total length classifications as proxies for life stages based on a length-at-age growth curve (Grabowski et al. 2008): juvenile (*juv*; ages 1–3; <469 mm), young adult (*ya*; ages 4–10; 469–638 mm), and old adult (*oa*; ages ≥11; >638 mm). We did not include life stages prior to juvenile in the estimation model because the RRCC database does not include data on early life stages.

Prior to analyzing the data, we removed capture records where the individual was not identified due to absence of tags or, in some cases, presence of tags was not checked (n = 21 for

Pee Dee, n = 116 for Savannah). We also removed (re)capture records with missing total length measurement (n= 5 for Pee Dee, n = 23 for Savannah). If an individual was recaptured multiple times, but length measurement was not recorded during one capture record, then the record is treated as if the fish was not detected. We then constructed a capture history for each individual in the dataset by assigning a state (juvenile = 1, young adult = 2, and adult = 3) to the fish during the year that it was captured based on its total length. If an individual was captured more than once within a year, we took the average of the total length measurements and based the state assignment on that average. For fish caught in multiple years, the size state assigned in a year was set equal to or greater than any state previously assigned, i.e., any reduction in total length measurement from a previous capture did not translate into a reduction in the animal's size state. If a fish was not captured during a sampling year, the fish was assigned a state indicating "not seen" (4). The capture history of an individual *i* in basin *k* consists of a vector of observation states over years *t*, $y_{i,t,k} \in \{1, 2, 3, 4\}$. Examples of two capture histories are as follows:

	Year 1	Year 2	Year 3	Year 4	Year 5
Fish 1	4	4	2	2	3
Fish 2	1	4	2	3	3

The observation (or non-detection) of an individual is a categorical outcome dependent on the true (and sometimes hidden) state of the individual ($z_{i,t,k}$; 1 = juvenile, 2 = young adult, 3 = old adult, 4 = dead). Survival probabilities for each stage were constant over time (*t*) but varied by basin (*k*). We did not estimate temporal or sex variability in survival probabilities because the management scenarios evaluated in the population viability analysis are not sex-specific in their effects. Year- and sex-dependent effects are also likely too small to be detectable with our sparse dataset. Lastly, sex information is not available for some individuals in the capture data, thus more capture data would need to be removed from the dataset if sex was being considered as a covariate in survival probability estimation.

Because an individual can stay within each life-stage from one year to the next depending on their age, only a proportion of individuals from one stage may transition into the next (Crouse et al. 2014). Therefore, we estimated the probability of an individual surviving and transitioning from the juvenile stage to young adult stage (G_{juv}) and the probability of surviving and transitioning from young adult to old adult (G_{yak}). The probability of surviving and remaining in the juvenile stage and in the young adult stage from one year to the next was indicated as P_{juv} and $P_{ya,k}$, respectively, and the transition and non-transition probabilities sum up to the survival probability of individuals of that stage:

$$\varphi_{juv} = P_{juv} + G_{juv}$$

$$\varphi_{ya,k} = P_{ya,k} + G_{ya,k}$$

Whereas we constrained transition probability from juvenile to young adult to be constant across time and basin due to parameter convergence issues, we allowed transition probability from young adult to old adult to be basin specific.

To account for variation in sampling conditions, methods, and effort which are unknown in many cases, we incorporated a random effect ($\varepsilon_{k,t}$) when estimating time- and basin-specific detection probabilities where the random effect of the detection probability from each basin follows a normal distribution with mean 0 and variance σ_k^2. During years when sampling was not conducted in a given unit, we set the detection probability within that year to 0 for that unit:

$$\begin{cases} logit(p_{k,t}) = \mu_k + \varepsilon_{k,t} \quad if\ sampling\ was\ conducted \\ p_{k,t} = 0 \quad if\ samplping\ was\ not\ conducted \end{cases}$$

$$\varepsilon_{k,t} \sim Normal(0, \sigma_k^2)$$

Due to limited data, especially for the juvenile stage, we used informed priors for survival probabilities of all life stages to help with parameter convergence. The informed priors follow beta distributions based on expert opinions elicited during SDM workshops. The priors for young adult and old adult survival probabilities followed a distribution of Beta(18, 3). The prior for juvenile survival probability followed a distribution of Beta(2, 3). All other priors followed a vague distribution of Uniform(0, 1). We used package *jagsUI* (Kellner 2019) in program R version 4.0.3 (R Core Team 2020) to conduct the analysis and ran 3 parallel chains with 100,000 iterations each, discarding the first 50,000 iterations as burn-in. We decided that parameter convergence was reached when trace plots of the MCMC samples showed good mixing and when R-hat values for all parameters were close to 1 (Gelman and Rubin 1992).

Population viability analysis

To evaluate management scenarios, we constructed a stage-based post-birth stochastic population model to project Robust Redhorse populations into the future under different scenarios for each management unit (Lefkovitch 1965). For each scenario, we projected the population 100 years into the future and ran the simulation for 1,000 iterations. The four life stages in our PVA model are age-0 (*yoy*), juvenile, young adult, and old adult (Figure 3.3). The model advances at one-year increments (t). The abundance of individuals in the juvenile, young adult, and old adult stages in the following year (N_{t+1}) are drawn using stochastic processes (i.e., Binomial and Multinomial) based on the abundance from current year (N_t), stage-specific survival rates (φ), probabilities of transition to the next stage (G), and probabilities of remaining in the current stage (P).

For Savannah and Pee Dee populations, we used the transition and remaining probabilities for juveniles and young adults obtained from the estimation model. For Altamaha and Broad populations, we calculated the probabilities from expert-elicited values of stage-specific survival probability (p_i) and number of years in the stage (d_i) using the formula proposed by Crouse et al. (1987) to calculate the probabilities:

$$P_i = \left(\frac{1 - p_i^{d_i - 1}}{1 - p_i^{d_i}}\right) p_i$$

$$G_i = \frac{p_i^{d_i}(1 - p_i)}{1 - \ p_i^{d_i}}$$

.

Because little is known about the recruitment potential of these populations, we used available information about egg production and an assumption about the adult population size that maximizes production of young to parameterize Ricker stock-recruitment relationships which are then used to generate recruitment of age-0 fish in the PVA. The Ricker stock-recruitment model is stated as follows:

$$R = aS^{-bS},$$

where R is the number of recruits, S is the number of spawning adults in the population, and a and b are density-dependent parameters that determine the shape of the spawning adult-recruit relationship (Ricker 1954). To determine the stock-recruitment relationship, we first assumed fecundity (N_{egg}; number of eggs produced by each female each year) is the same for young and old adults and is based on the average number of eggs collected from females as part of RRCC's annual egg collection effort in the Oconee River for spawning and rearing fish in captivity (RRCC unpublished data). We then calculated number of age-0 fish produced per adult female in the population by multiplying N_{Egg}, probability of egg survival to become young-of-the-year (φ_{egg}), and 0.5 to get per capita recruitment (F):

$$F = N_{egg} \times \varphi_{egg} \times 0.5$$

We then multiplied age-0 recruits per adult by the adult abundance at which the population would be at its most productive (750 individuals) to get the total number of age-0 recruits each year, which is set as the maximum recruits on the baseline Ricker curve. Using the solver function in Excel, we solved for the a and b parameters of the Ricker curve (Figure 3.12). We then generated 1,000 Ricker curves (one for each iteration of the PVA) by drawing 1,000 sets of a and b values from a multivariate normal distribution using the original a and b parameter values as means.

For a given management unit, we used the same initial abundance for each stage for all scenarios and iterations. The initial abundances of old adults in the populations are based on expert opinion (Table 3.6), and initial abundances for all other stages are calculated based on stable-stage distribution of population size, using the eigenvector to calculate abundance in other stages given initial old adult abundance (Lefkovitch 1965).

Management Scenarios and Consequences

Similar to performance metrics (Table 3.1), potential management actions also varied among the spatial management units (Tables 3.2 – 3.5). We included a status quo scenario reflecting the current management status for each unit. The status quo scenario in the Altamaha and Broad populations include visual monitoring of spawning activities. In Altamaha, status quo also includes run-of-the-river flow during spawning and rearing seasons. Savannah's status quo scenario includes visual surveys of spawning activities. The status quo scenario in Pee Dee includes stocking age-0 fish into the population every year. Other potential management scenarios consist of either a single management action or a combination of actions. For the Altamaha (Table 3.2) and Broad (Table 3.3) management units, the stakeholders considered management actions including stocking of age-0 fish, manipulating water flow regime to improve spawning conditions, and regulating bowfishing. Stocking scenarios envisioned for these two populations involved immediately adding between 1,000 and 5,000 age-0 fish each year either (1) only for 5 years or (2) only for 25 years. For Savannah (Table 3.4), stakeholders identified management scenarios that included 1) manipulating water flows to improve spawning conditions and 2) increasing connectivity between habitat patches currently separated by hydropower dams (e.g., building fish passageways), either singly or in combination. They also considered status quo and habitat management in the absence and presence of climate change. Stocking has been the main management action implemented for the Pee Dee population thus far (Table 3.5). Therefore, stakeholders contemplated two scenarios for stocking age-0 fish: (1) stocking targets of 13,000-17,000 met every year, or (2) stocking targets of 13,000-17,000 and 1,000-3,000 met in alternating years (status quo). The stakeholders also added a scenario where stocking did not occur, as well as a scenario with no stocking in the presence of climate change to compare the results from the stocking strategies.

For stocking scenarios in all management units, we simulated augmentation of age-0 fish into the population on top of naturally recruited age-0s by drawing a random number from a gamma distribution matching the target number stocking abundance. To determine potential population responses to other management actions, we asked the stakeholders to hypothesize effects of each management action on life stages (using size classes as proxies). The stakeholders hypothesized that adjusting flow regime in the river during the spawning and rearing season could potentially increase recruitment and survival of age-0 fish. Increasing connectivity between habitats in the Savannah would increase access to ideal spawning habitats, therefore the management action is thought to increase age-0 recruitment. Lastly, regulating bowfishing activities could potentially increase survival probability of old adults in the Altamaha and Broad because the old adults are thought to be more vulnerable to incidental takes by bow fishermen (Tables 3.2 – 3.5).

To account for the consequences of management actions on recruitment of age-0 fish, we simulated different Ricker stock-recruit relationships to be used under different scenarios by changing egg survival (φ_{egg}). The baseline (i.e., "medium") Ricker recruitment described under the *Population Viability Analysis* section is used under scenarios that are not hypothesized to result in changes to egg survival and thus recruitment of age-0 fish (i.e., status quo, stocking only, and bowfishing regulation). We then followed the same procedure used to generate the medium recruitment to simulate "low" recruitment to represent lower egg survival ($\varphi_{egg} = 0.0025$) which is applied to scenarios where age-0 recruitment is negatively affected (i.e., under climate change), as well as "high" recruitment scenarios ($\varphi_{egg} = 0.0075$) where management actions improved recruitment of age-0 fish into the population. In all recruitment scenarios, maximum reproductive potential occurs when the reproductive adult (young and old adults) abundance reaches 750 individuals (Figure 3.4). Beyond this level, recruitment may decrease due to superimposition of eggs within a spawning habitat which may lead to decreased egg and larvae survival (C. Straight, U.S. Fish and Wildlife Service, personal communication). Under scenarios with actions thought to improve age-0 survival (e.g., water flow adjustment), we doubled age-0 survival for that scenario. If two management actions are implemented to improve age-0 survival within a scenario (e.g., water flow adjustment and increase connectivity), then we quadrupled age-0 survival under said scenario.

Even with density dependent recruitment imposed on the simulations, the initial population projections for Pee Dee and Savannah reached levels higher than what is reasonable according to experts. Therefore, we adjusted age-0 survival in the PVA for those populations until the average abundance of reproductive adult populations towards the end of the simulation under the status quo scenario more closely matched values that the experts believed to be more reasonable based on their observations.

Performance metrics calculation

To summarize performance of different management scenarios, we quantified model outputs corresponding to the performance metrics specified by stakeholders (Table 3.1). For average adult abundance over time, we averaged reproductive adult (both young and old adults) abundance across simulations for each year of the simulation to demonstrate population trend. For the summary performance statistics that included the average adult abundance over the last 25 years of the simulation, we took the average of adult abundance across the *last 25 years* of each iteration in the PVA and graphed the results as a bar graph to demonstrate the variation among iterations of the outcomes for all management scenarios. Population growth rates were calculated by dividing population size at next time step (N_{t+1}) by population size at current time step (N_t). We used the threshold of 0 individuals to evaluate population persistence at the end of the simulation. For each iteration within a scenario, we assign a persistence value of 1 to the population if the total abundance was above 0 during the last year, and 0 if abundance reached 0. We then took the average across the 1,000 iterations of the simulation within each management scenario to calculate the percentage of iterations where populations persisted.

Parametric uncertainty

To incorporate parametric uncertainty in the PVA, we sampled input values of population parameters at every iteration of the simulation as well as every year within a simulation either from posterior distributions of the multistate models (Savannah and Pee Dee) or from expert-based distributions (Altamaha and Broad). Due to limited knowledge about stage-specific survival probabilities for Altamaha and Broad populations, we applied a blanket uncertainty around the parameters by drawing input values from a uniform distribution with mean ± 20% as the range. For parameter values that were estimated from the multistate model, we drew values from the MCMC samples from the Bayesian model output. For consistency among populations that possessed or lacked empirically estimated parameters, we did not vary transition probabilities among simulations or years. Although the transition probabilities remain fixed through the simulations, numbers of individuals transitioning into young and old adult stages each year are nevertheless stochastic because they are sampled from multinomial distributions.

To further investigate how the uncertainty associated with population parameters affect the outcome of the PVA, we conducted sensitivity analysis by changing one population parameter incrementally while holding every other parameter constant to examine how the adjustments affected performance metrics such as population size and growth rate. We focused the sensitivity analysis on the status quo scenario of the Pee Dee population to be able to examine the effect of changes in parameter values on the PVA outcome. All analyses were conducted in program R version 4.0.3 (R Core Team 2020).

Results

Stage-specific population parameters

The capture-mark-recapture dataset for Robust Redhorse included sampling data from 2001 – 2021 for the Pee Dee population, with a sampling hiatus in 2011 and 2012, and data from 1998 – 2018 for the Savannah population. Overall, 559 unique individuals were included in the analyses, including 206 from the Pee Dee population and 353 from the Savannah population.

The survival probability of juveniles (φ_{juv}) for Savannah and Pee Dee populations was estimated as 0.45 (SD = 0.14; 95% BCI 0.19 – 0.75) and 0.33 (SD = 0.18; 95% BCI 0.05 – 0.73), respectively (Figure 3.5). Estimates of young-adult (φ_{ya}) and old-adult survival probabilities (φ_{oa}) were comparable to expert opinions for Pee Dee, while the estimates for Savannah were slightly lower compared to expert opinion (Table 3.6; Figure 3.5). The transition probability from juvenile to young adult (G_{juv}) and from young adult to old adult (G_{ya}) were 0.33 (SD = 0.13; 95% BCI 0.11 – 0.61) and 0.18 (SD = 0.04; 95% BCI 0.11 – 0.26), respectively for Pee Dee. Those same parameters were estimated as 0.24 (SD = 0.15; 95% BCI 0.03 – 0.60) and 0.10 (SD = 0.03; 95% BCI 0.05 – 0.16) for Savannah. Mean detection probability (p) of Robust Redhorse was higher (0.19; SD = 0.05; 95% BCI 0.10 – 0.30) in Pee Dee compared to that of Savannah (0.04; SD = 0.02; 95% BCI 0.01 – 0.08). Consequently, low detection probability in Savannah led to slightly higher uncertainty around estimates of adult survival probabilities (Figure 3.5).

PVA outcomes

In Altamaha, none of the scenarios resulted in reproductive adult population of 1,000 individuals at the end of the simulation, which was a target set by the stakeholders during the SDM workshop (Figures 3.6 – 3.7). On the other hand, population persistence (i.e., probability that there is at least one Robust Redhorse left in the population at the end of the simulation) was 0 for the scenarios that did not include water flow adjustment, whereas persistence was 1 for all scenarios with adjusted water flow (Figure 3.8). Lastly, average population growth rate towards the end of the simulation was 0 under scenarios without water flow adjustment and 1 under scenarios with water flow adjustment (Figure 3.9).

In Broad, the scenarios that included water flow adjustment and bowfishing regulation resulted in reproductive adult abundance above the target of 300 individuals, while the scenarios that only included stocking did not meet the target (Figures 3.6 – 3.7). However, population persistence and growth rate were both 1 for all scenarios in Broad (Figures 3.8 – 3.9).

The reproductive adult population of 1,000 individuals was projected to meet the target set by the Committee under all scenarios except for the status quo and climate change scenarios in the Savannah management unit (Figure 3.6 – 3.7). The scenario with increase in habitat connectivity, water flow adjustment, and climate change performed better compared to scenarios with only increase in habitat connectivity or only water flow adjustment in terms of average reproductive adult abundance. Probability of persistence for the population meets the target set by stakeholders (0.95) for all scenarios except for the climate-change scenario (Figure 3.8).

The probability of persistence for the population in Pee Dee was 1 for the stocking and no stocking scenarios (Figure 3.8). However, the probability of persistence for the population was much lower when stocking did not occur under climate change (Figure 3.8). Furthermore, none of the scenarios resulted in reproductive adult abundance that met the target set by the Committee (Figures 3.6 – 3.7).

Sensitivity analysis

Our sensitivity analysis revealed that varying young-of-the-year (age-0) and old adult survival probabilities over a range of values incrementally did not result in different probability of persistence for the Pee Dee population (Figure 3.10). In fact, probability of persistence remains 1 over the range of age-0 and old adult survival probabilities used for the analysis. Alternatively, the population growth rate decreased as we increased age-0 and old adult survival probabilities (Figure 3.11).

Discussion

Due to the vulnerability of threatened and endangered species to environmental changes and uncertainty associated with their management, making decisions through a documentable and transparent process is critical. For this study, we worked closely with the RRCC and led the Committee through a structured decision-making process to develop an adaptive management framework for conserving Robust Redhorse, an endangered freshwater fish in Georgia and North Carolina. We collaboratively completed many of the steps of structured decision making, including developing a problem statement through evaluating potential consequences. Although we do not consider this a complete cycle of adaptive management, the steps presented here can be used to inform the selection of management actions that could then be combined with learning to reduce decision-relevant uncertainties and provide a framework for adaptive management.

Two common modeling tool kits are often used in the structured decision-making process: population parameter estimation models and population viability analysis models (Crawford et al. 2018; Saunders et al. 2018; McGowan et al. 2020; Folt et al. 2021). In this study, we analyzed existing capture data of Robust Redhorse in the Savannah and Pee Dee drainages to estimate stage-specific survival and transition probabilities, which we subsequently used in the population viability analysis. For Altamaha and Broad units, we relied on expert-elicited values for the PVA. The PVA revealed that the Altamaha management unit faces possibility of extirpation without management actions that increase age-0 survival in the system, such as adjusting water flow that improves spawning and rearing habitats during the respective seasons. PVA results from the other three management units showed persistent populations at the end of the simulation period under all management scenarios. However, when the effect of climate change on recruitment was included with the status quo scenario and no stocking scenarios for the Savannah and Pee Dee populations, respectively, the estimated probability of persistence fell below the 95% threshold set by the stakeholders.

Our multistate Cormack-Jolly-Seber model provided stage-specific survival probabilities for the Savannah and Pee Dee populations. There is relatively little known about the survival probabilities of Robust Redhorse; the most recently published adult survival was by Jennings et al. (2000), in which they estimated annual apparent survival probability of adults in the Oconee River between 0.1 (SE ±0.02) and 0.99 (SE ±0.00) for years 1995 – 1998. Our model-estimated young and old adult survival probabilities for both Pee Dee and Savannah are comparable to those from other long-lived sucker species (Janney et al. 2008; Hewitt et al. 2010; Young and Koops 2014; Chapter 2 in this dissertation). However, estimates of juvenile survival probability for Savannah and Pee Dee were highly uncertain, even after incorporating informed priors in the model based on expert opinion. This is due to few captures of juveniles (n = 24) throughout the sampling period for both basins. One potential explanation for low juvenile captures is the size selectivity of the sampling methods. Most of the captures were conducted using electrofishing boats, which have been shown to capture larger fish compared to other sampling methods (Anderson 1995). Additionally, whether juvenile Robust Redhorse use the same habitat as adults is unclear. Experiments testing for habitat preference of larval and juvenile Robust Redhorse showed that they prefer deeper pools, such as eddies and backwater in the rivers during the winter and spring (Weyers et al. 2003b; Mosley and Jennings 2007). These habitats are not typically sampled using electrofishing boats. Instead, backpack electrofishers may be more efficient in sampling areas such as backwaters of a river (Mosley and Jennings 2007). Detection probabilities of Robust Redhorse in both Pee Dee and Savannah are low, and Savannah detection probability was lower compared to Pee Dee. This could be due to the removal of capture records from the dataset prior to analysis, although the estimated detection probability for the Savannah population in this study is similar to that from a study examining capture probability of Robust Redhorse in the Ocmulgee River, GA (Grabowski et al. 2009).

The results from our PVA demonstrated the importance of evaluating a suite of potential management actions aside from scenarios with a single management action. Stocking has been used as a primary management tool for returning Robust Redhorse to self-sustaining populations within its range. However, our PVA showed that stocking alone may not be sufficient at meeting management objectives for Robust Redhorse populations. In Altamaha, scenarios that only included stocking had population growth rate > 1 in the beginning and middle of the simulation period and ultimately led to population crashes, whereas scenarios that included stocking and improving rearing habitat quality led to persistent populations (Figures 3.8–3.9). This demonstrates that while stocking is effective in boosting population size for a short period of time, the viability of the population still depends on habitat quality. Therefore, to best utilize limited resources, it may be more efficient to establish self-sustaining populations where stocking will not be needed in the future by implementing actions that also improve habitat conditions. Another approach to make the stocking program more effective could be stocking older fish. The majority of fish stocked in the Robust Redhorse populations have been young-of-the-year, which have lower survival probability compared to older individuals (e.g., juveniles). On the other hand, rearing fish in captivity until they reach the juvenile stage leads to higher cost for the stocking program. Weighing these factors when implementing future stocking programs to select the "biggest bang for the buck" option would be beneficial for stakeholders. Similar comparisons of population augmentation techniques have been conducted in other species. For example, Daly et al. (2018) compared individual growth rate and conditions of Desert Tortoise (*Gopherus agassizii*) hatchlings released into the wild for population augmentation and found that hatchlings that were reared in captivity grew faster compared to those that were reared outdoor before release and those that were released immediately after hatching (Daly et al. 2018). The Robust Redhorse stocking program in North Carolina has stocked both phase I (6 month old) and phase II (18 months old) fish into the Pee Dee River (North Carolina Wildlife Resources Commission 2020). However, the relative success of different stocking strategies, and how they could change over time, is another uncertainty that could be targeted by future studies.

Considering other environmental changes that do not involve management actions in future scenarios, such as changes in land use (Tucker et al. 2021), drought conditions (Howell et al. 2020; Crawford et al. 2022), and seasonal temperature (Bastille-Rousseau et al. 2018) is common practice when conducting PVAs. In our decision analysis for the Savannah and Pee Dee populations, we included vital rate scenarios expected to be brought about by climate change to examine their effect on Robust Redhorse. Experiments have demonstrated that juvenile Robust Redhorse experienced increased thermal stress as water temperature increased from 20°C to 35°C (Walsh et al. 1998). Furthermore, higher percentage of larval deformities, some of which are fatal, also occur among Robust Redhorse when water temperature is higher than optimal (21°C – 23°C;

RRCC 1999). In both Savannah and Pee Dee populations, the climate change scenarios were assumed to have low recruitment potential and thus resulted in the lowest probability of persistence and 0 adults at the end of the simulations when additional conservation actions were not taken (Figures 3.6 – 3.8). However, increasing habitat connectivity and improving spawning habitats (water flow adjustment) in the context of climate change resulted in higher reproductive adult abundance compared to the status quo, increase in connectivity, and water flow adjustment scenarios. Therefore, impact of climate change, which is assumed to result in rise in water temperature that negatively affects recruitment, could potentially be offset by conservation measures that increase spawning habitat and improve its quality if some recruitment offsets were realized.

Sensitivity analyses help decision makers visualize the importance (or non-importance) of parametric uncertainty on comparing consequences of alternative anticipated outcomes. In our sensitivity analysis, we did not find that probability of persistence was sensitive to changes to age-0 or old adult survival probabilities in the PVA. More specifically, probability of persistence of the Pee Dee population under the status quo scenario (i.e., stocking target met every other year) remains 1 over the range of values used in the sensitivity analysis. However, adult abundance increased with age-0 and old adult survival probabilities, and consequently changed the outcome of the scenario relative to management targets. For example, average adult abundance at the end of the simulation is below the 500 individual target set by the Committee when age-0 survival was below 0.004 and above the target when age-0 survival is above 0.004 (Figure 3.10). For the sensitivity analysis, we took the average of mean population growth rate over all simulation years (i.e., years 1–100). However, the resulting patterns may be different if we averaged the population growth rate over a different time period (e.g., years 80–100). This result demonstrates that probability of persistence and growth rate may not be the best metrics to evaluate during sensitivity analysis in this particular case. Instead, metrics such as quasi-extinction or extirpation probability that measures probability of a population declining to a non-zero threshold could be more informative (Tucker et al. 2021; Crawford et al. 2022).

We were able to complete many components of the SDM process, but future iterations of the same process may be needed to increase understanding of early-life stage dynamics and population responses to implemented management actions. Further iterations of the SDM process, particularly discussion about the biology of the species and consequences of management actions, could help improve the scenario-forecasting tool for Robust Redhorse populations. For example, in our PVA, we applied the same recruitment patterns to all populations. In reality, the carrying capacity and peak reproductive potential may occur at different adult population sizes due to variation in the quantity and quality of spawning habitat. Additionally, due to constraints in the type of population simulation model used, we were not able to include account for genetic diversity in our PVA. A potential improvement to the PVA could be including genetic diversity for populations where it is known (e.g., Pee Dee) when simulating stocking scenarios and avoid genetic swamping (Tringali and Bert 1998).

We demonstrated the utility of the SDM process in developing the "start-up" phase of an adaptive management framework (Williams and Brown 2012) for an imperiled freshwater fish. For RRCC to adopt a full AM approach, we suggest that the stakeholders proceed with the "iterative" phase of AM, which includes making recurrent management decisions at a set frequency (e.g., every year or every three years), focusing on management actions that could help reduce uncertainty, and monitoring population response to said actions to gain new information for future decision making. In the case of Robust Redhorse, a recurrent decision to be made could be augmenting existing populations in each unit. The stocking decision could be state-dependent, in that the decision whether to stock or number of fish to stock depends on current adult abundance and evidence of recruitment.

A key uncertainty that could be reduced using AM is structural uncertainty (incomplete understanding of response of the system to an action). A commitment to collecting and using monitoring data to reduce structural uncertainty is a required component in the adaptive management process (Canessa et al. 2016). An effective monitoring program requires clear hypotheses and questions that managers can attempt to answer (Nichols and Williams 2006; Lindenmayer and Likens 2009). For example, one of the key unknowns about Robust Redhorse populations currently is the factors affecting survival and recruitment of younger fish which hinders effective management of the species. Innovative monitoring methods that would help biologists better link population data to environmental covariates could greatly help reduce uncertainty surrounding how Robust Redhorse populations respond to environmental changes and management actions, an understanding now based solely on expert opinions. For example, monitoring methods that could help biologists infer abundances of age-0 and juvenile Robust Redhorse in the population and how they vary with changes to environmental variables such as water temperature and water flow can help quality their effects on early life stages of Robust Redhorse. Additionally, a refined monitoring protocol for adult Robust Redhorse could also help better our understanding in its status. An adult Robust Redhorse monitoring protocol that ensures every fish released is tagged and that the tag IDs are recorded upon every recapture event could result in more complete dataset and help safeguard against misidentification of individuals over time. Prior to analyzing the mark-recapture data, we had to remove some capture records of fish that did not have an ID associated with the record. As such, some information regarding survival and recapture probability was lost in the process. Multistate mark-recapture models can be "data-hungry" in that complete capture histories of individuals are needed to obtain parameters that are more precise, especially if factors such as sex and environmental covariates are to be included in the model to help elucidate their effects on population parameters. Additionally, failure to record the ID of a tagged fish upon capture could also negatively bias survival probabilities when modeling the population.

Additionally, AM can help account for, though not necessarily reduce, the following uncertainties: environmental variation, uncertainty about population states (partial observability), and uncertainty around how a planned management action will be implemented in reality (partial controllability; Williams et al. 1996; Johnson et al. 2015; Canessa et al. 2016). Partial observability in Robust Redhorse applies to current state of the populations, including abundance of fish in each life stage with each management units. Lack of such information impedes biologists' ability to effectively manage the populations as the decision regarding which actions to implement may depend on population size. In terms of partial controllability, implementation of stocking programs can be affected by factors outside of the managers' control. For example, higher than usual mortality of larval and age-0 fish could occur in the hatchery rendering the program not meeting its stocking targets (B. Jones, North Carolina Wildlife Resources Commission, unpublished data).

Application of SDM and AM is widespread in fish and wildlife population management. In this study, we completed steps in the structured decision-making process with stakeholders of the Robust Redhorse Conservation Committee to guide the decision-making process through evaluating potential management scenarios. Currently, there are few adaptive management frameworks developed for conserving threatened or endangered sucker species (but see Kesner et al. 2016). The decision-making analysis that we conducted with Robust Redhorse could support development of an adaptive management framework for the RRCC, and similar structures could be applicable to conserving other Catostomid species in the future.

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Table 3.1. Management objectives, performance metrics, and reference-point values for each Robust Redhorse management unit tracked by the population viability analysis. Only objectives with performance statistics that were evaluated by the PVA are presented in the table. Other objective (i.e., adaptive potential) and performance statistics are presented in Appendix A.

Means Objectives	**Performance statistics**	**Altamaha**	**Broad (GA)**	**Savannah**	**Pee Dee**
Stable or increasing population size	% of starting adult population size at end of simulation (relative metric - +, -, or =)	increasing	stable	stable	increasing
	Population growth rate over simulation period (lambda)	Average lambda >1	Average lambda >1	Average lambda >1	Average lambda >1
Population persistence	Probability of persistence (calculate from PVA) over simulation period	>0.95	>0.95	>0.95	>0.95
Self-sustaining population	Average adult abundance over last 25 years of simulation	1000	300	1000	500

Table 3.2. Consequence table for Robust Redhorse population in Altamaha management unit, including scenarios and expert-elicited parameter values.

Management Scenarios	**Age-0 Recruitment**	**φ_{yoy} mean (range)**	**φ_{juv} mean**	**φ_{ya} mean**	**φ_{oa} mean (range)**
Status quo	Medium	0.01 (0.008-0.012)	0.5	0.55	0.75 (0.7-0.8)
Stocking only (first 5 years)	Medium	0.01 (0.008-0.012)	0.5	0.55	0.75 (0.7-0.8)
Stocking only (first 25 years)	Medium	0.01 (0.008-0.012)	0.5	0.55	0.75 (0.7-0.8)
Flow adjustment	High	0.01 (0.016-0.024)	0.5	0.55	0.75 (0.7-0.8)
Stocking (5 years) + flow adjustment	High	0.02 (0.016-0.024)			
Stocking (25 years) + flow adjustment	High	0.02 (0.016-0.024)	0.5	0.55	0.75 (0.7-0.8)
Bowfishing regulation	Medium	0.01 (0.008-0.012)	0.5	0.55	0.9 (0.85-0.95)

Table 3.3 Consequence table for Robust Redhorse population in Broad management unit, including scenarios and expert-elicited parameter values.

Management Scenarios	**Age-0 Recruitment**	**φ_{yoy} mean (range)**	**φ_{juv} mean**	**φ_{ya} mean**	**φ_{oa} mean (range)**
Status quo	Medium	0.01 (0.008-0.012)	0.5	0.8	0.8 (0.75-0.85)
Stocking only (first 5 years)	Medium	0.01 (0.008-0.012)	0.5	0.8	0.8 (0.75-0.85)
Stocking only (first 25 years)	Medium	0.01 (0.008-0.012)	0.5	0.8	0.8 (0.75-0.85)
Flow adjustment	High	0.01 (0.016-0.024)	0.5	0.8	0.8 (0.75-0.85)
Stocking (5 years) + flow adjustment	High	0.02 (0.016-0.024)			
Stocking (25 years) + flow adjustment	High	0.02 (0.016-0.024)	0.5	0.8	0.8 (0.75-0.85)
Bowfishing regulation	Medium	0.01 (0.008-0.012)	0.5	0.8	0.9 (0.85-0.95)

Table 3.4. Consequence table for Robust Redhorse population in Savannah management unit, including scenarios and hypothesized and estimated parameter values. A range of values was provided for the parameters elicited from experts, and 95% credible intervals were provided for parameters estimated from the multistate Cormack-Jolly-Seber model.

Management Scenarios	**Age-0 Recruitment**	**φ_{yoy} mean (range)**	**φ_{juv} mean (95% BCI)**	**φ_{ya} mean (95% BCI)**	**φ_{oa} mean (95% BCI)**
Status quo	Med	0.0075 (0.006 – 0.009)	0.33 (0.05 – 0.73)	0.81 (0.73 – 0.89)	0.72 (0.62 – 0.81)
Flow adjustment	High	0.015 (0.012 – 0.018)	0.33 (0.05 – 0.73)	0.81 (0.73 – 0.89)	0.72 (0.62 – 0.81)
Increase connectivity	Med	0.015 (0.012 – 0.018)	0.33 (0.05 – 0.73)	0.81 (0.73 – 0.89)	0.72 (0.62 – 0.81)
Flow + Connectivity	High	0.03 (0.024 – 0.036)	0.33 (0.05 – 0.73)	0.81 (0.73 – 0.89)	0.72 (0.62 – 0.81)
Status quo + climate change	Low	0.0075 (0.006 – 0.009)	0.33 (0.05 – 0.73)	0.81 (0.73 – 0.89)	0.72 (0.62 – 0.81)
Flow + connectivity + climate change	Med	0.03 (0.024 – 0.036)	0.33 (0.05 – 0.73)	0.81 (0.73 – 0.89)	0.72 (0.62 – 0.81)

Table 3.5. Consequence table for Robust Redhorse population in Pee Dee management unit, including scenarios and hypothesized and estimated parameter values. A range of values was provided for the parameters elicited from experts, and 95% credible intervals were provided for parameters estimated from the multistate Cormack-Jolly-Seber model.

Management Scenarios	Age-0 Recruitment	φ_{yoy} mean (range)	φ_{juv} mean (95% BCI)	φ_{ya} mean (95% BCI)	φ_{oa} mean (95% BCI)
Status quo (Stocking goal met every other year)	Med	0.002 (0.0016 – 0.0024)	0.45 (0.19 – 0.75)	0.91 (0.82 – 0.97)	0.84 (0.79 – 0.90)
Stocking goal met every year	Med	0.002 (0.0016 – 0.0024)	0.45 (0.19 – 0.75)	0.91 (0.82 – 0.97)	0.84 (0.79 – 0.90)
No stocking	Med	0.002 (0.0016 – 0.0024)	0.45 (0.19 – 0.75)	0.91 (0.82 – 0.97)	0.84 (0.79 – 0.90)
No stocking + climate change	Low	0.002 (0.0016 – 0.0024)	0.45 (0.19 – 0.75)	0.91 (0.82 – 0.97)	0.84 (0.79 – 0.90)

Table 3.6. Input parameter values and their sources for the population viability analysis for each Robust Redhorse management unit.

Parameter	Altamaha	Broad (GA)	Savannah	Pee Dee	Source
Initial abundance (old adult)	20	25	100	50	Expert elicitation
Initial abundance (young adult)	49	132	631	122	Calculated from stable-stage distribution
Initial abundance (juvenile)	163	1755	3836	408	Calculated from stable-stage distribution
Initial abundance (age-0)	6524	15115	37924	16309	Calculated from stable-stage distribution
Old adult survival probability	0.75	0.8	0.72	0.84	Expert elicited for Altamaha and Broad. Model estimated for Savannah and Pee Dee
Young adult survival probability	0.55	0.8	0.81	0.91	Expert elicited for Altamaha and Broad. Model estimated for Savannah and Pee Dee
Juvenile survival probability	0.5	0.5	0.334	0.454	Expert elicited for Altamaha and Broad. Model estimated for Savannah and Pee Dee
Age-0 survival probability	0.01	0.01	0.0075	0.002	Expert elicited for all, but adjusted for Savannah and Pee Dee to align PVA adult abundance output with expert expectations
Egg survival probability	0.005	0.005	0.005	0.005	Expert elicitation
Number of eggs/young adult female/year (YA)	30000	30000	30000	30000	Hatchery data
Number of eggs/old adult female/year (OA)	30000	30000	30000	30000	Hatchery data
juvenile transition probability	0.019	0.041	0.245	0.33	Calculated from stable-stage distribution based on expert elicited parameters for Altamaha and Broad. Estimated for Savannah and Pee Dee
young adult transition probability	0.007	0.053	0.098	0.18	Calculated from stable-stage distribution based on expert elicited parameters for Altamaha and Broad. Estimated for Savannah and Pee Dee

Table 3.7. Comparison between expert opinion of juvenile, young adult, and old adult survival probabilities and model estimates of the same parameters for Pee Dee and Savannah populations.

Population parameter	**Expert opinion**	**Model-estimated mean (95% BCI)**
Pee Dee juvenile survival (φ_{juv})	0.5	0.45 (0.19–0.75)
Savannah juvenile survival (φ_{juv})	0.5	0.33 (0.05–0.73)
Pee Dee young adult survival (φ_{ya})	0.9	0.91 (0.83–0.97)
Savannah young adult survival (φ_{ya})	0.9	0.81 (0.73–0.90)
Pee Dee old adult survival (φ_{oa})	0.9	0.85 (0.79–0.90)
Savannah old adult survival (φ_{oa})	0.9	0.72 (0.62–0.81)

Table 3.8. Comparison of Robust Redhorse adult population size at the beginning and end of the simulation for each management unit under all scenarios. A “–” indicates adult population at the end is less compared to starting population, a “+” indicates adult population at the end is more than starting population, and a “=” indicates adult population at the end is same as starting population.

Population	**Management Scenarios**						
	Status quo	Stock 5	Stock 25	Flow	Stock 5 & flow	Stock 25 & flow	Bowfishing reg
Altamaha	–	–	–	+	+	+	–
	Status quo	Stock 5	Stock 25	Flow	Stock 5 & flow	Stock 25 & flow	Bowfishing reg
Broad	+	+	+	+	+	+	+
	Status quo	Connectivity	Flow	Flow & conn	Climate change	Flow & conn & climate	
Savannah	=	+	+	+	–	+	
	Stock target met every other yr	Stock target met every yr	No stocking	No stocking & climate			
Pee Dee	+	+	+*	–			

*average reproductive adult abundance for the no stocking scenario in Pee Dee is only slightly higher at the end of the simulation compared to the beginning.

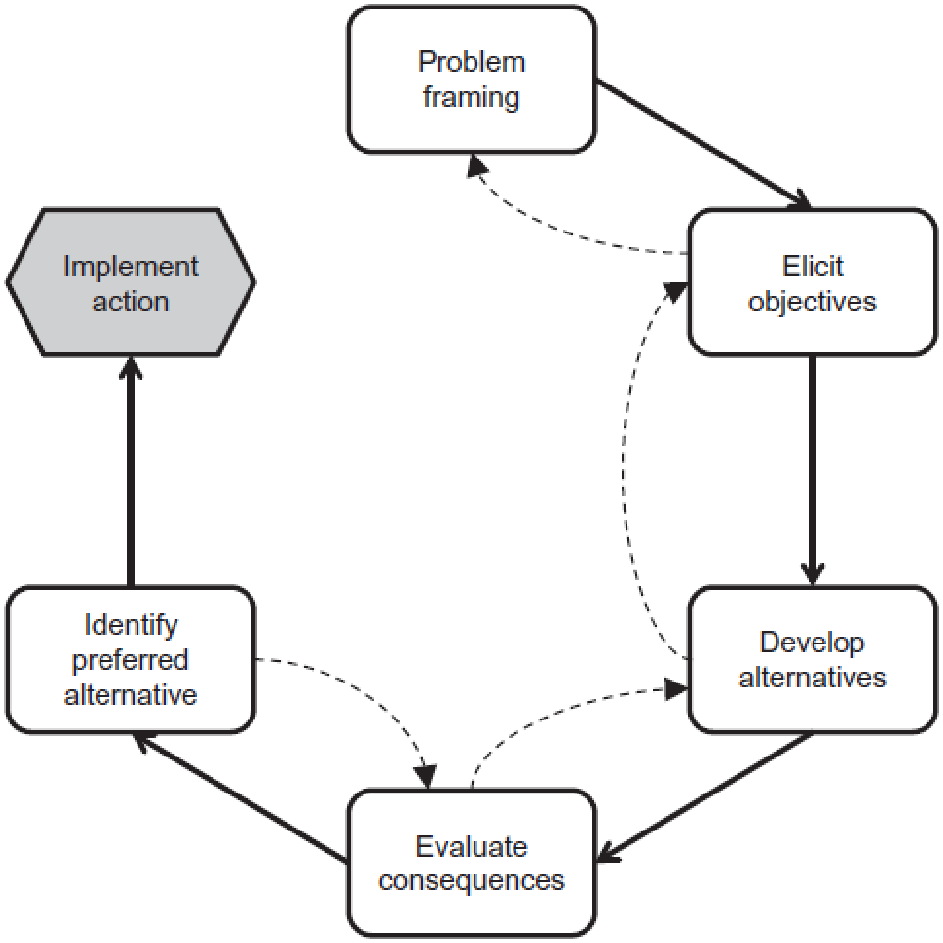

Figure 3.1. The steps in a typical structured decision-making process. Black arrows represent directions of the steps, whereas dashed arrows represent opportunities to revisit previous steps as needed. Figure from Runge et al. (2013).

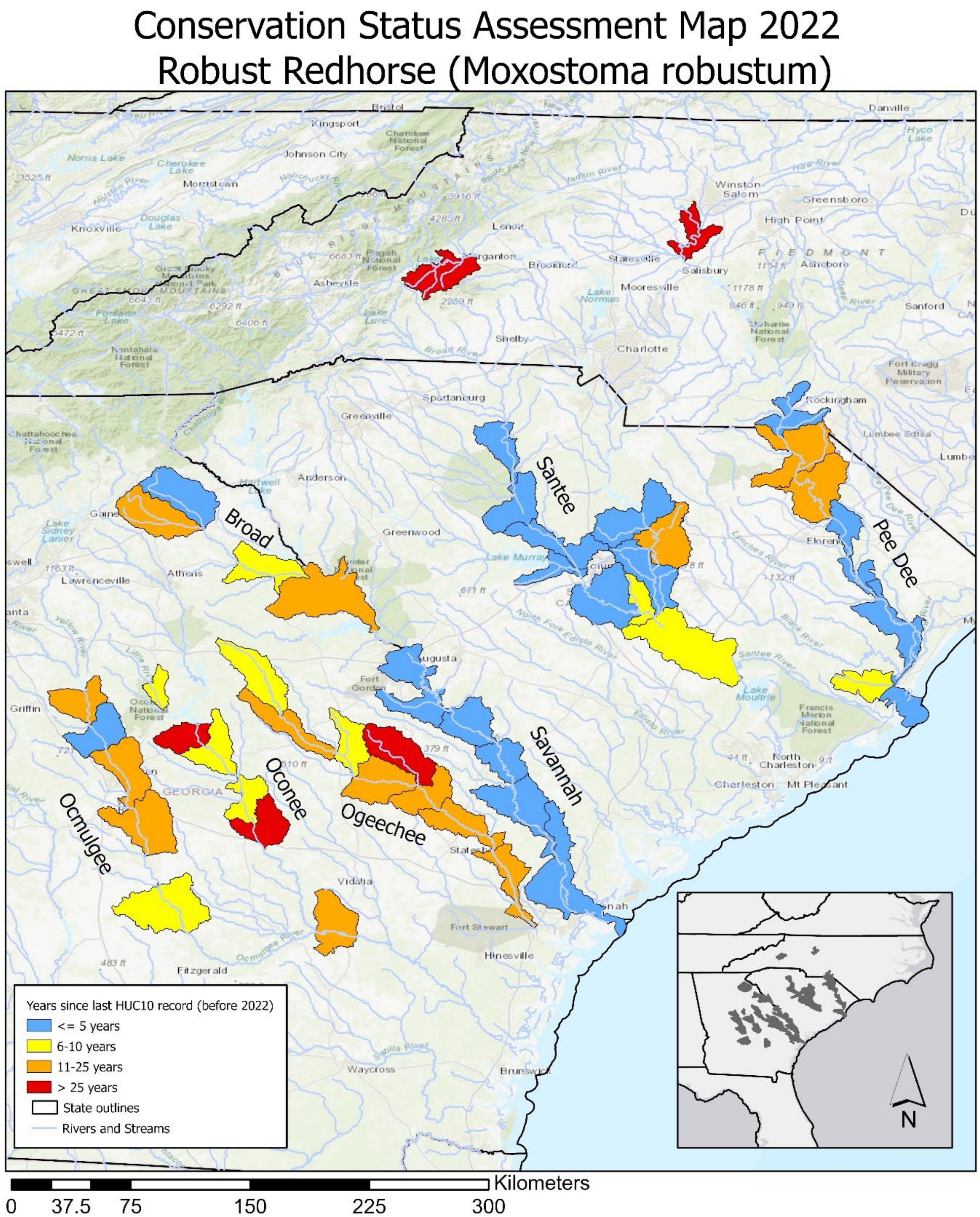

Figure 3.2. Current (as of 2022) range map of the Robust Redhorse populations. Map produced by Georgia Department of Natural Resources.

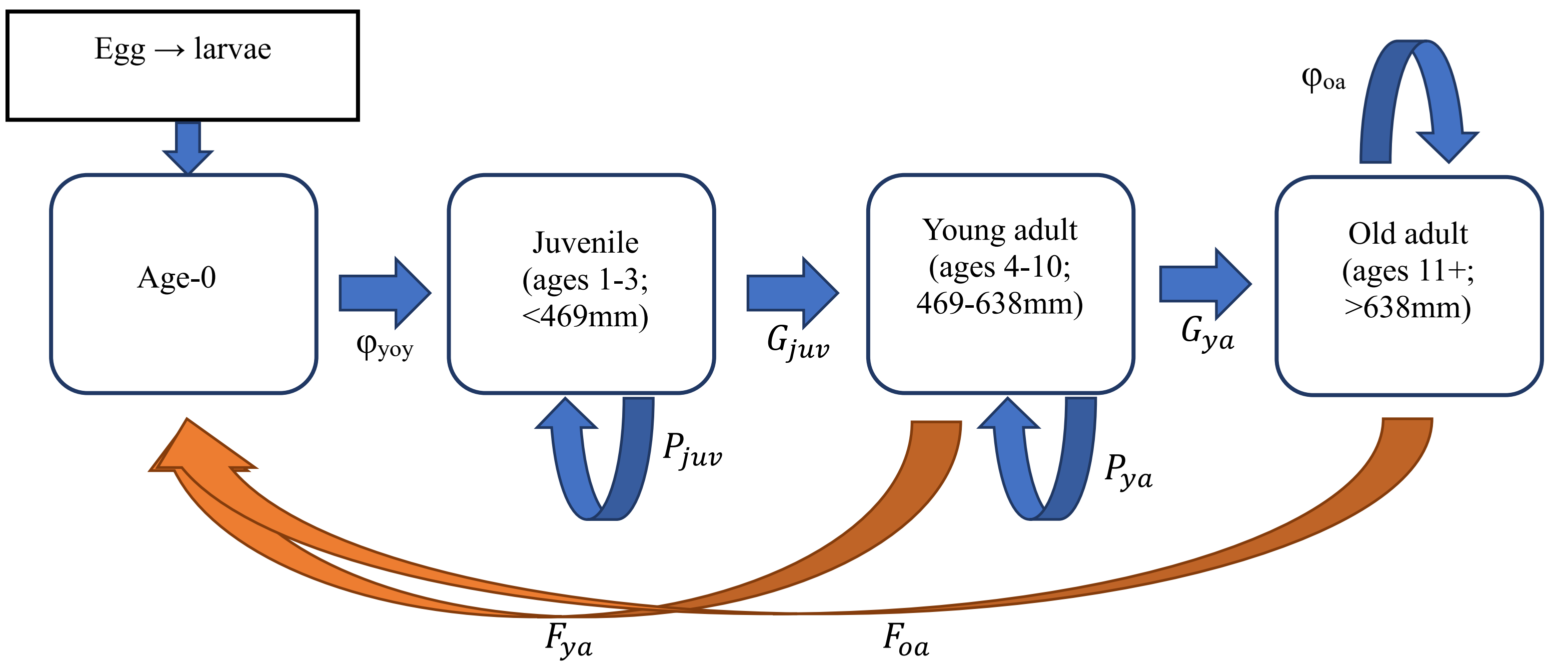

Figure 3.3. Illustration of the stage-based model for simulating Robust Redhorse population projections. φ_{yoy} = age-0 survival, P_{juv} = probability of juveniles remaining juveniles in the following year, G_{juv} = probability of juveniles transitioning to the young adult stage, P_{ya} = probability of young adults remaining young adults, G_{ya} = proportion of young adults that transition into old adults, φ_{oa} = survival of old adults, F_{ya} = young-adult fecundity, F_{oa} = old-adult fecundity.

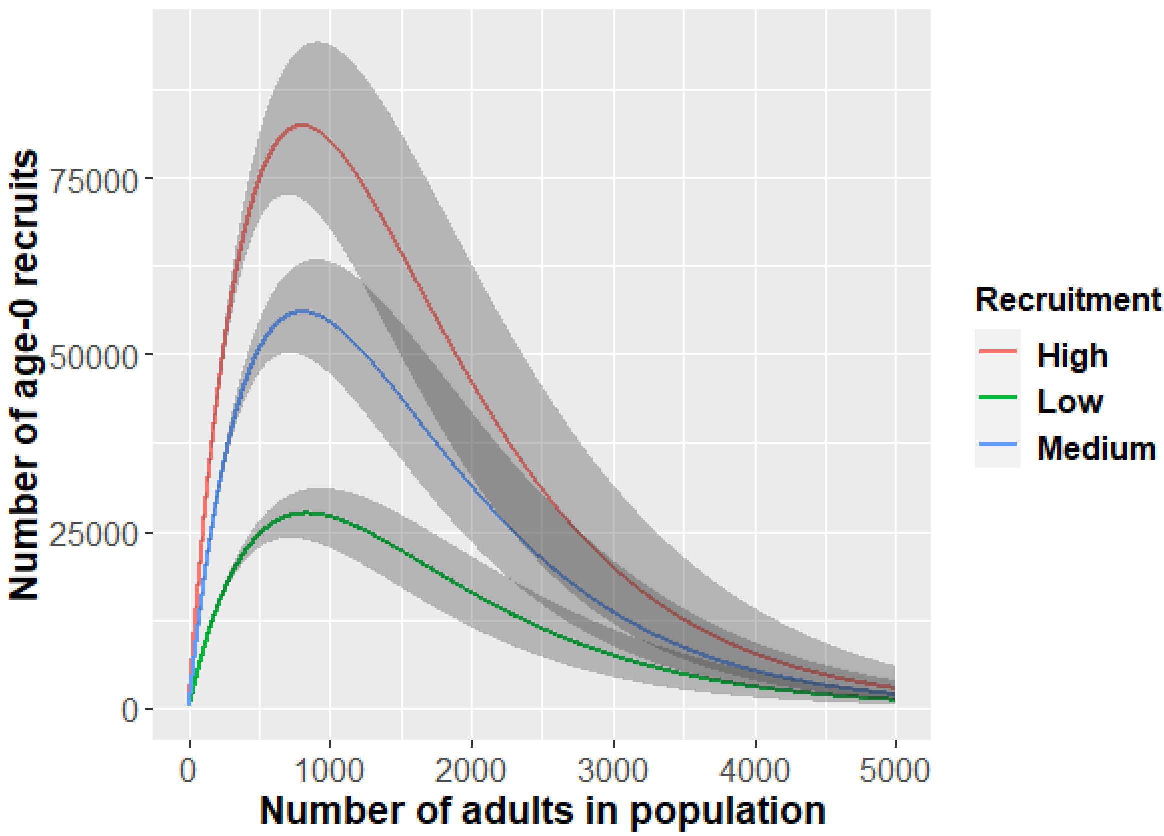

Figure 3.4. Ricker recruitment curves for low, medium, and high recruitment scenarios. Colored lines represent the mean of the simulated Ricker curves for each level of recruitment, gray areas represent the range of number of age-0 recruits corresponding to the reproductive adult population size.

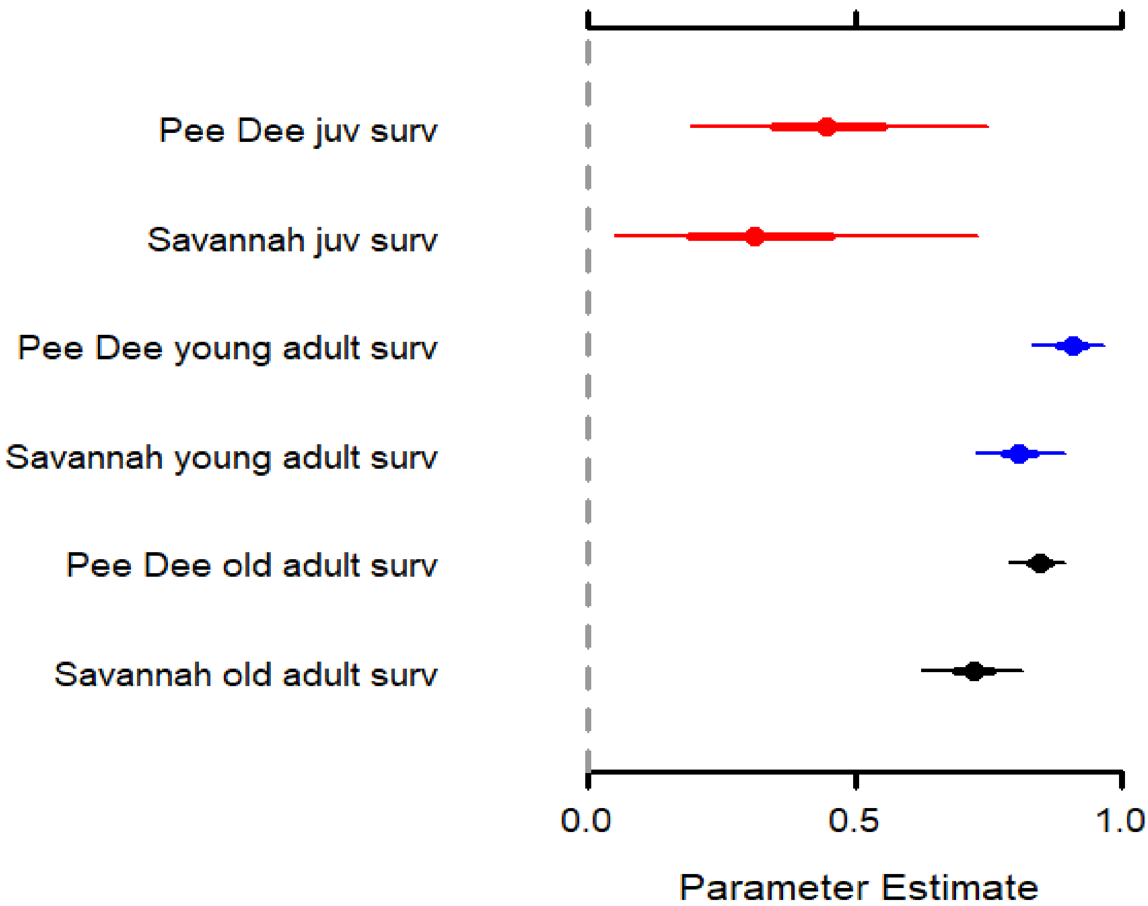

Figure 3.5. Stage-specific survival probabilities for Robust Redhorse in Pee Dee and Savannah management units. Colored dots are means of the posterior samples from the Bayesian model, thick lines are 50% Bayesian credible intervals, and thin lines are 95% Bayesian credible intervals.

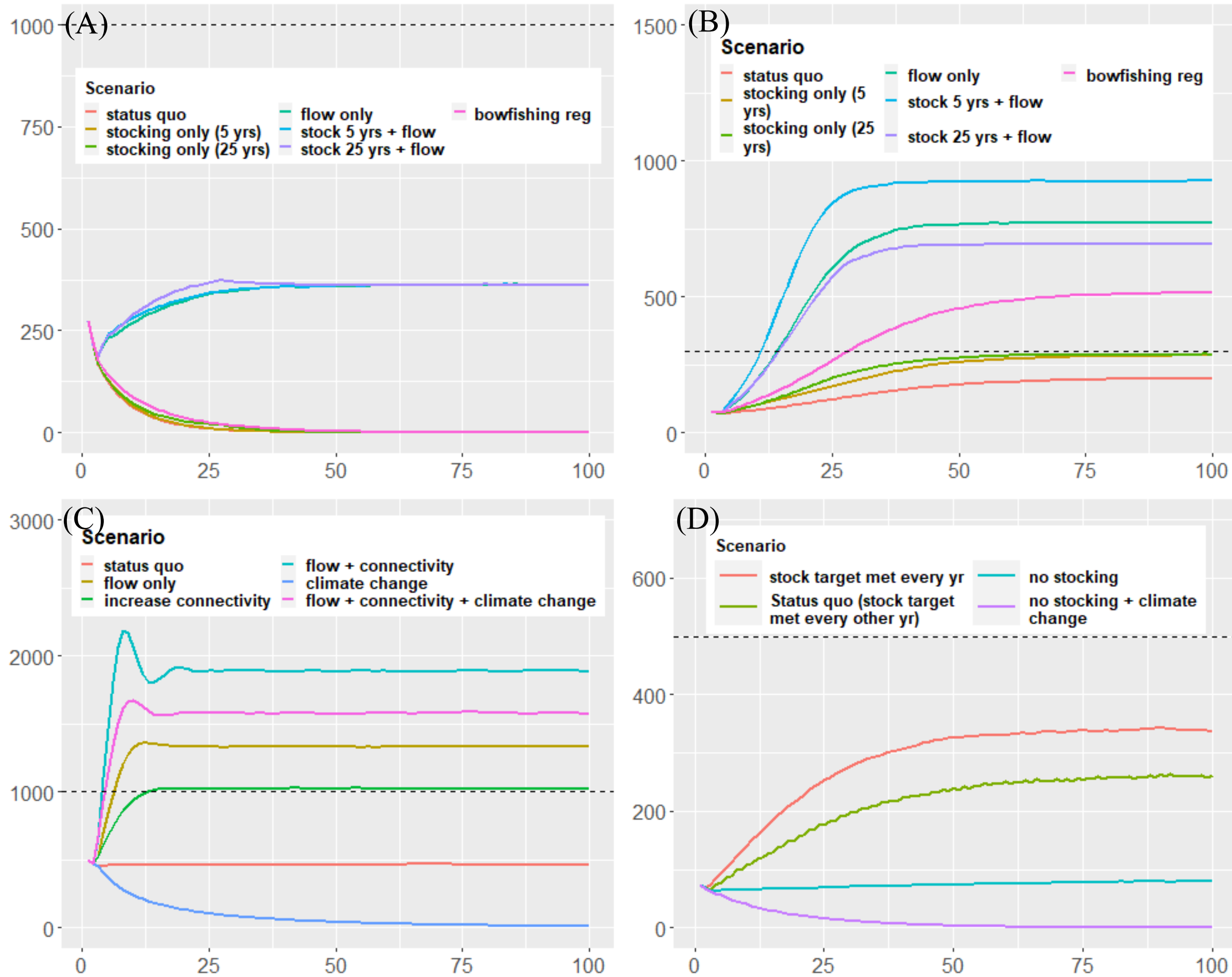

Figure 3.6. Projected average reproductive adult (ages 4+) abundance under different scenarios for Robust Redhorse in A) Altamaha, B) Broad, C) Savannah, and D) Pee Dee management units. Dashed lines represent the unit-specific target for the performance metric for evaluating management actions.

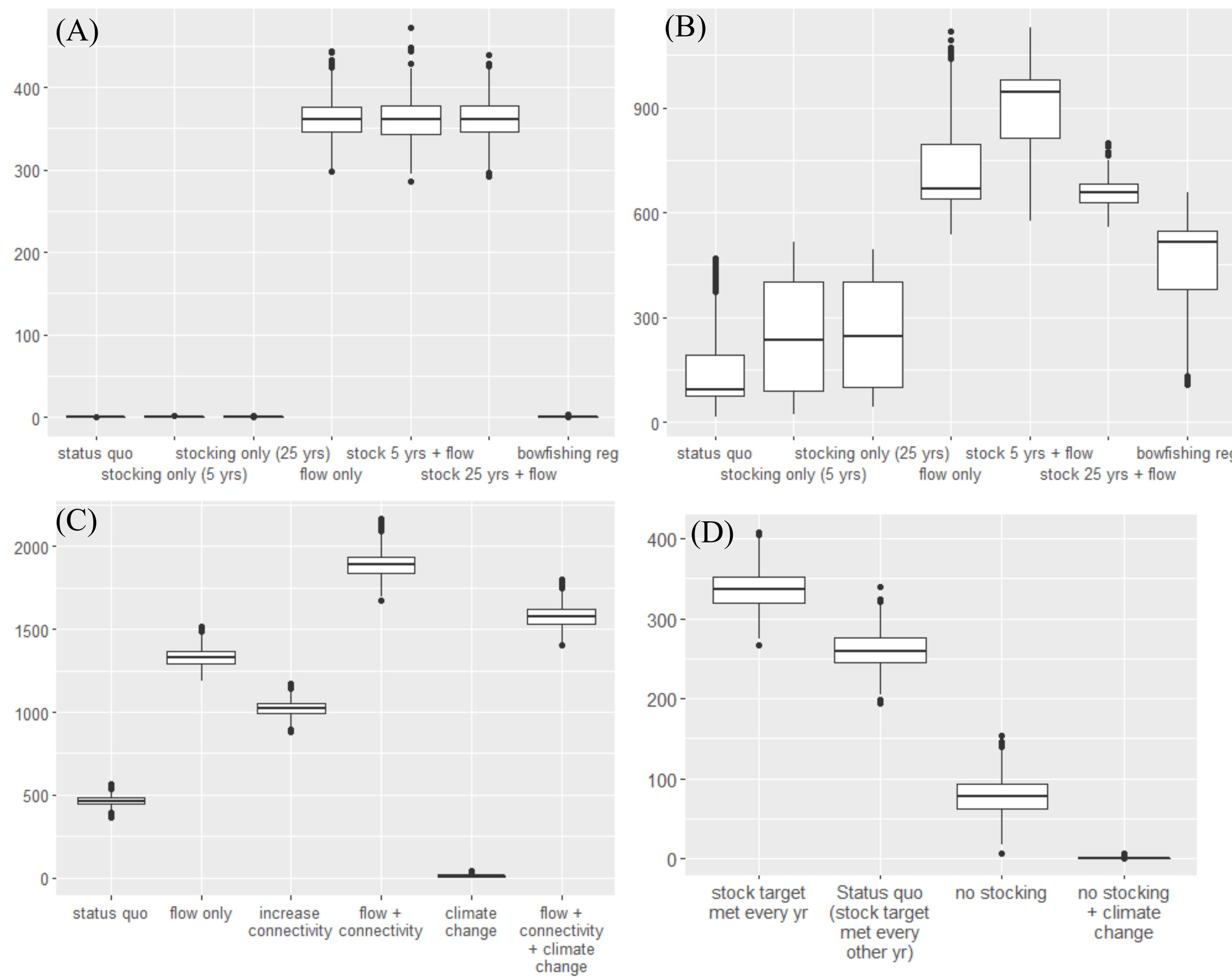

Figure 3.7. Box plot of reproductive adult (ages 4+) abundance under different scenarios averaged across the last 25 years of each simulation (n = 1,000) for Robust Redhorse in A) Altamaha, B) Broad, C) Savannah, and D) Pee Dee management units.

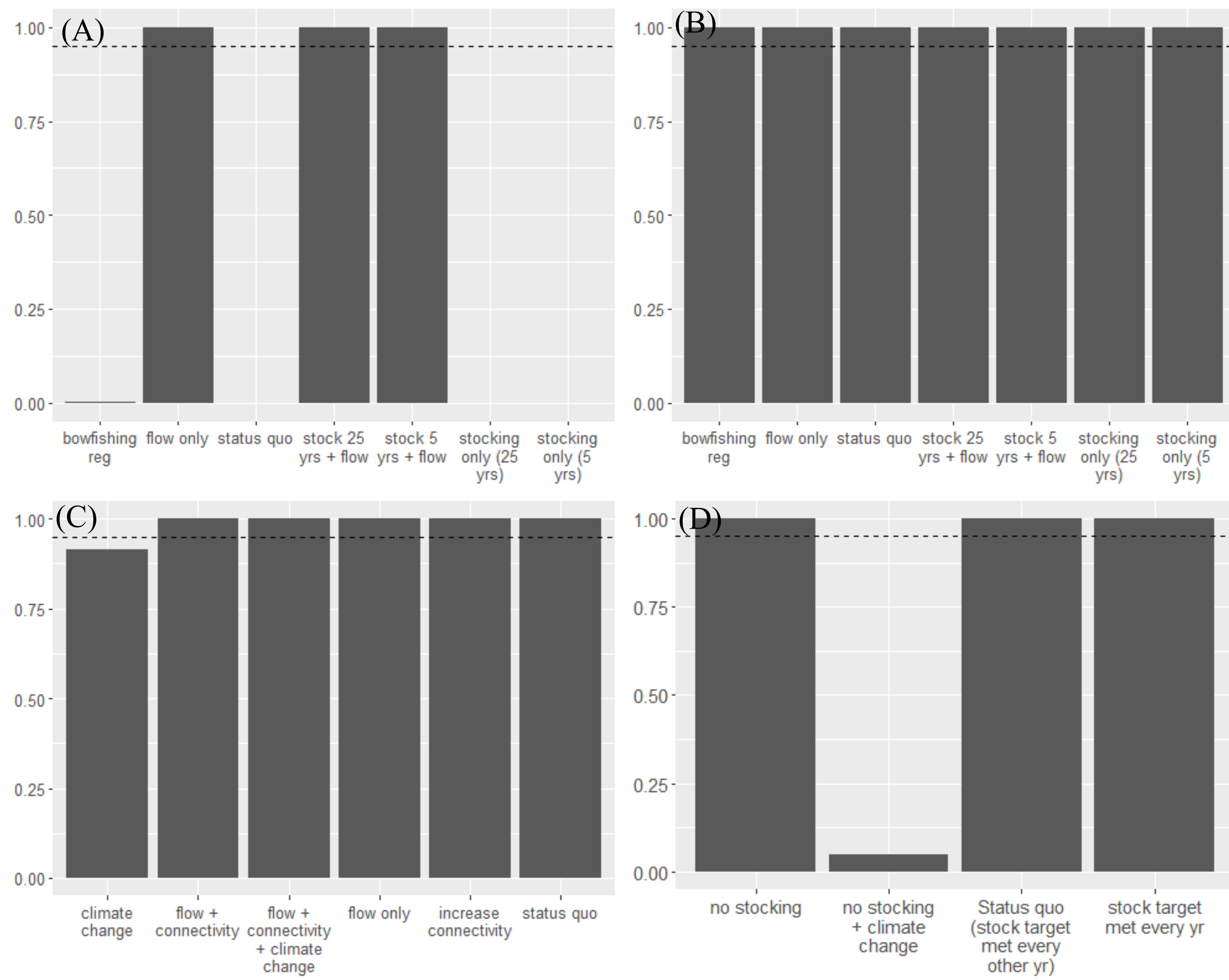

Figure 3.8. Projected population persistence under different scenarios for Robust Redhorse in A) Altamaha, B) Broad, C) Savannah, and D) Pee Dee management units. Dashed lines represent the unit-specific target for the performance metric for evaluating management actions.

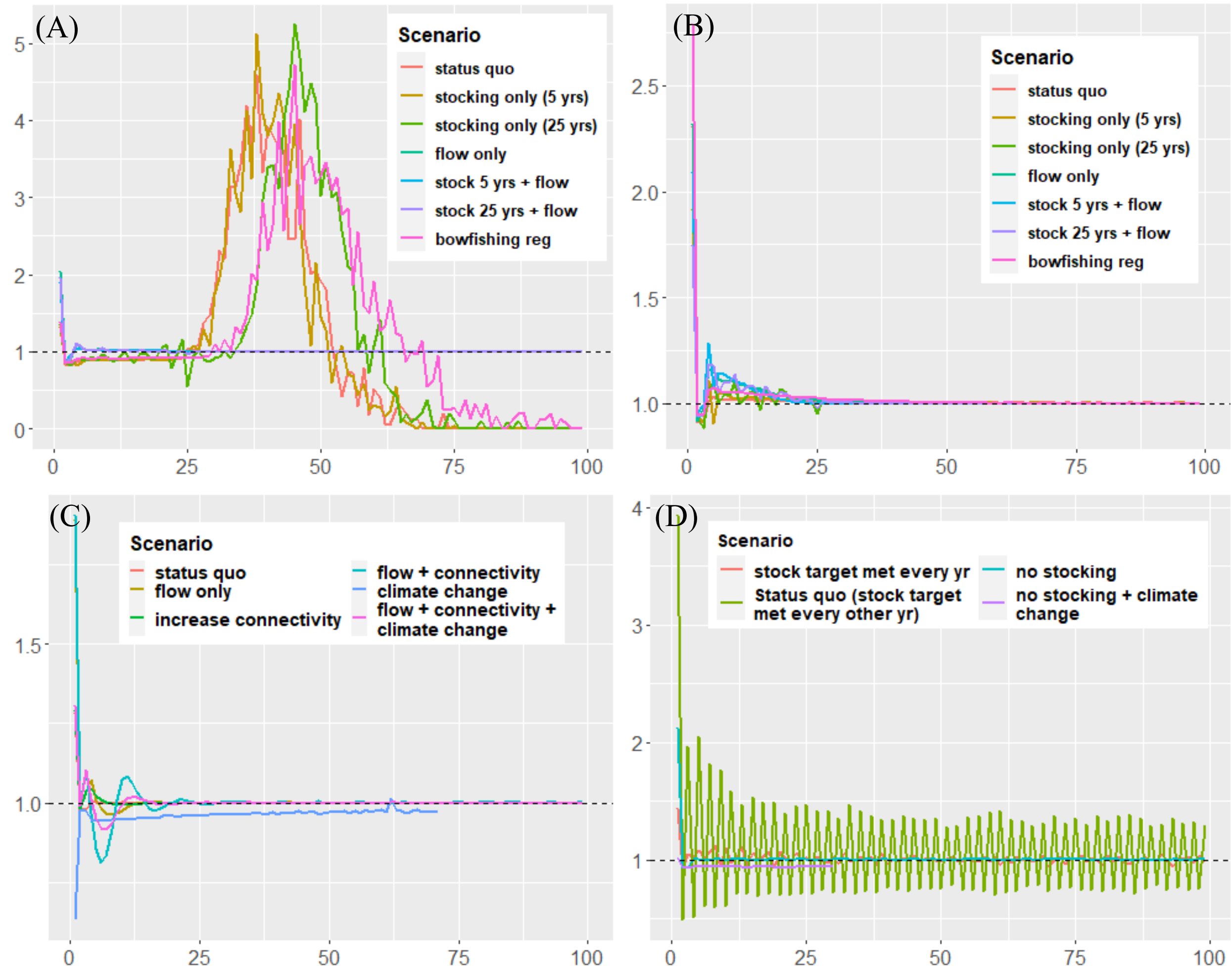

Figure 3.9. Projected average population growth rate (lambda) under different scenarios for Robust Redhorse in A) Altamaha, B) Broad, C) Savannah, and D) Pee Dee management units. Dashed lines represent the unit-specific target for the performance metric for evaluating management actions.

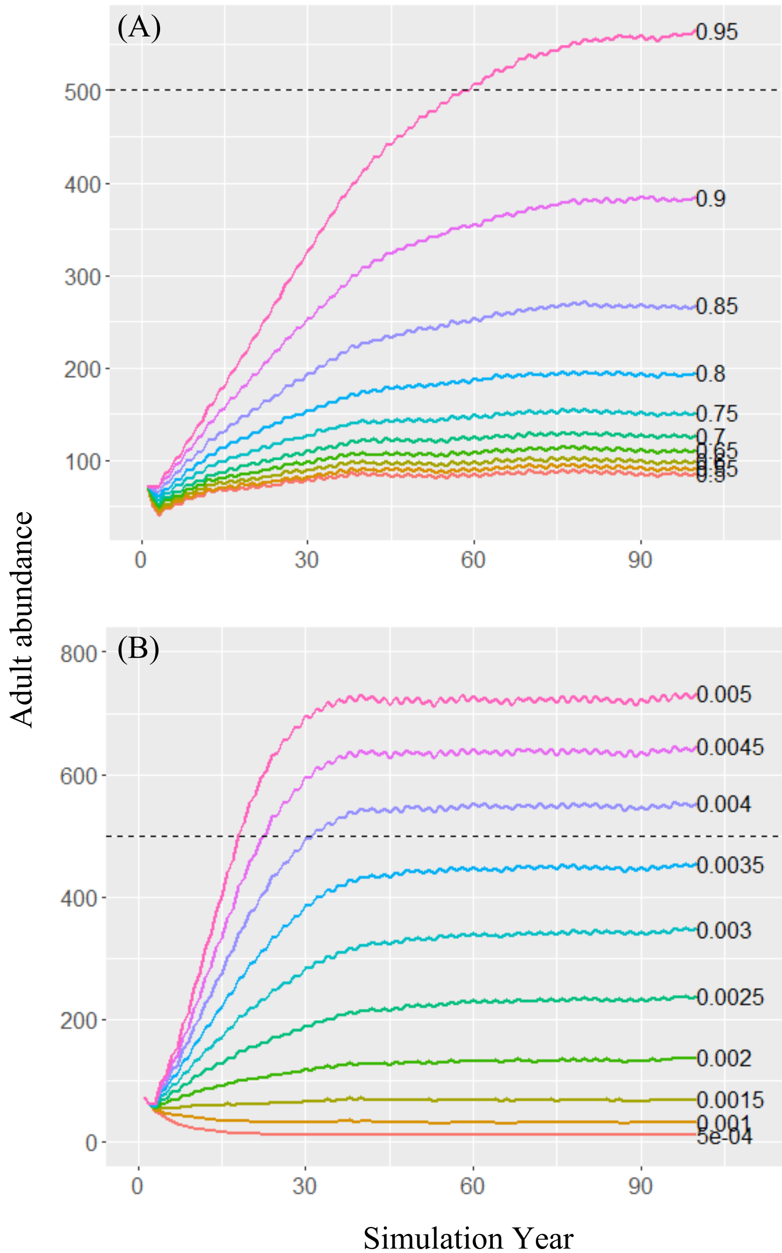

Figure 3.10. Abundance of reproductive adult Robust Redhorse in Pee Dee based on PVA outcomes using a range of A) age-0 survival probabilities (0.0005 – 0.0025) and B) old adult survival probabilities (0.5 – 0.95) during sensitivity analysis. Dashed line represents the abundance target.

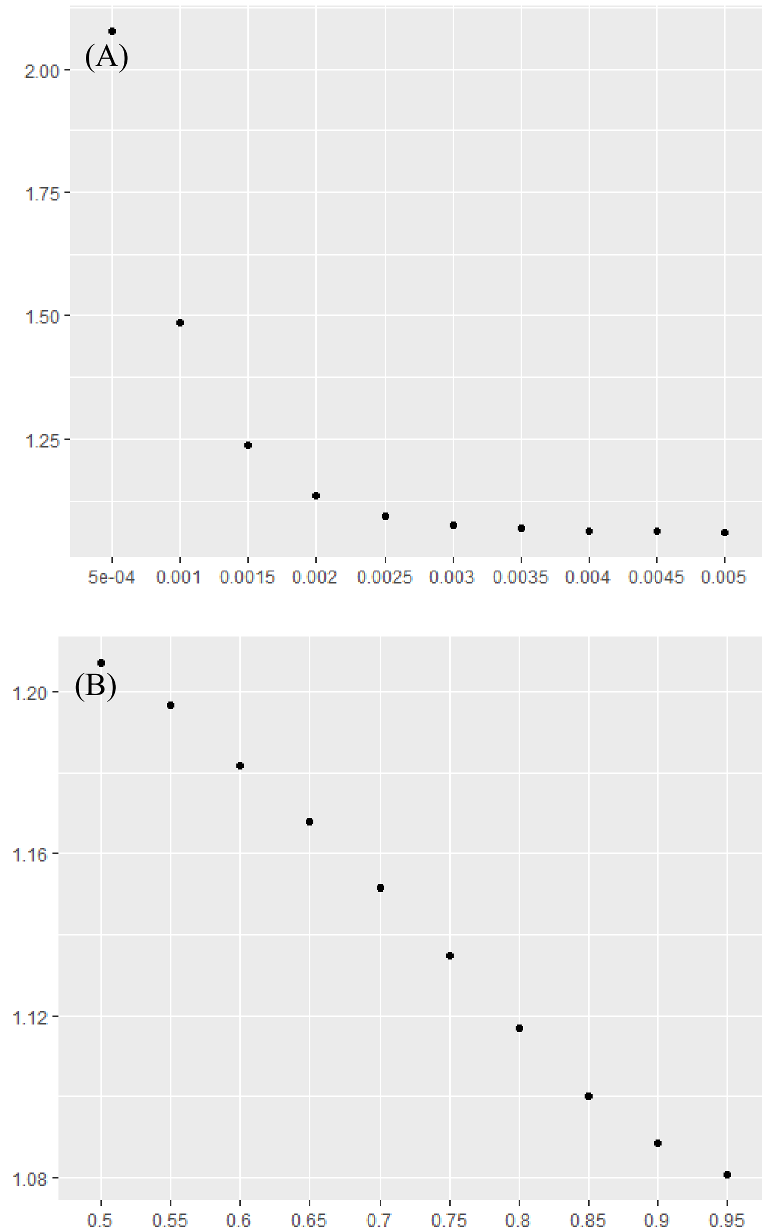

Figure 3.11. Population growth rates averaged across simulation and time for Robust Redhorse in Pee Dee based on PVA outcomes using a range of A) age-0 survival probabilities (0.0005 – 0.0025) and B) old adult survival probabilities (0.5 – 0.95) during sensitivity analysis.

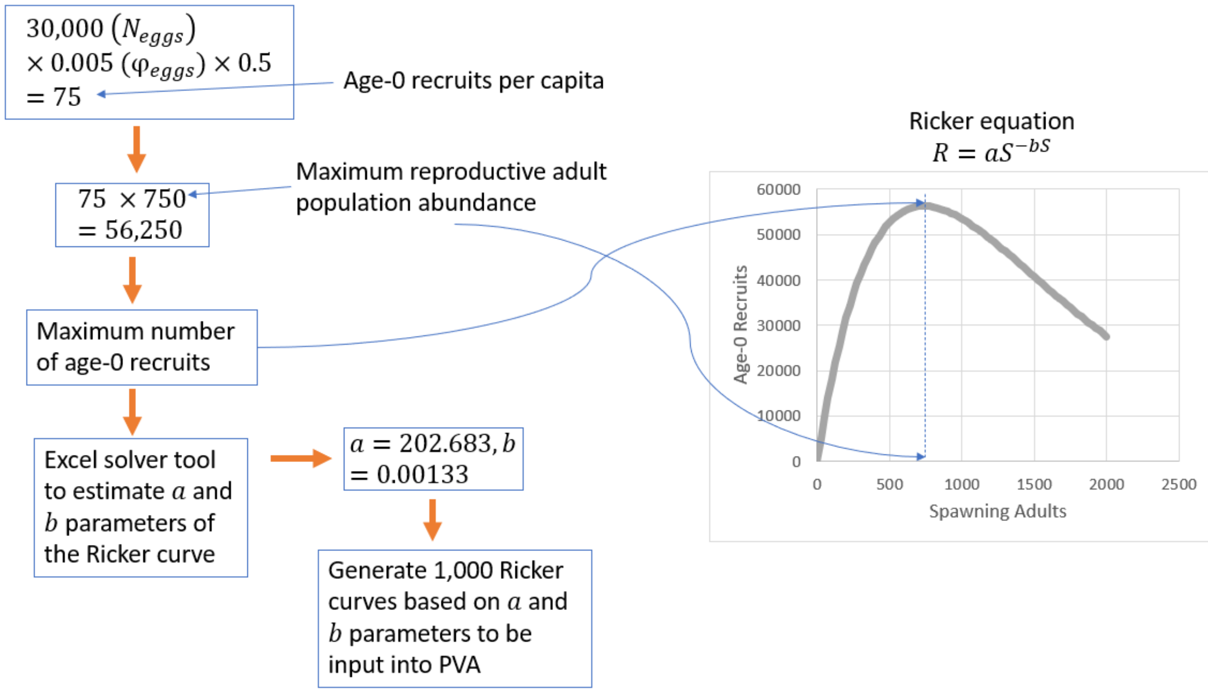

Figure 3.12. Workflow for generating Ricker spawning adult-recruitment relationships representing total number of age-0 fish recruits in the population over a range of spawning adult abundance. Example depicted is the workflow used to generate the base-line Ricker relationship used in the population viability analysis.

CHAPTER 4

ASSESSING SOCIAL LEARNING PROCESS AND OUTCOME IN CONSERVATION OF AN IMPERILED FISH SPECIES [3]

[3]Hsiung, A. C., Irwin, B., and Nelson, D. To be submitted to *Journal of Environmental Management.*

Abstract

Social learning has garnered much attention as a mechanism for increasing adaptive capacity of environmental governance. Despite its importance, the role of social learning in threatened and endangered species conservation is rarely studied. We examined social learning outcomes and factors affecting social learning under the context of conservation of an imperiled freshwater fish, Robust Redhorse (*Moxostoma robustum*) and used the Robust Redhorse Conservation Committee (RRCC) as a case study. We also investigated whether social learning led to collective actions from RRCC members to address conservation issues of Robust Redhorse. Our findings demonstrated that social learning occurred among RRCC members through deliberation and collaboration. Outcomes of social learning included instrumental learning where new knowledge and skills were gained by both individuals and the group and relational learning, such as trust building and professional network expansion. We found that factors related to group dynamics (e.g., diversity) as well as process (e.g., conflict resolution, quality of interactions) affected learning. Our results also indicated that social learning led to collective actions taken by the RRCC members, including management actions such as stocking and habitat improvement to aid in the recovery of Robust Redhorse populations. Our study provides an example of social learning in species conservation and management and the lessons learned may be applicable to similar contexts.

Introduction

Conservation practitioners have becoming increasingly aware of the interconnectedness and complexity of the social-ecological system under which they operate. In the complex environment full of uncertainty, environmental governance requires adaptive capacity to cope with unexpected disturbances. Social learning, whereby a diverse stakeholder group co-produces knowledge and understanding surrounding an environmental problem through collaboration and deliberation, could potentially help increase the adaptive capacity of environmental governance and promote system resilience (de Kraker, 2017; Pahl-Wostl, 2009).

While many studies recognize the importance of social learning in participatory and adaptive environmental governance, there is not a consensus among scholars on its definition (Gerlak et al., 2019a, 2018; Reed et al., 2010). Social learning theories can be traced back to the fields of transformative and experiential learning (Muro and Jeffrey, 2008). Transformative learning can be defined as "a reflective process that enables an individual's perceptions and consciousness to be altered" and experiential learning as "a process of creating knowledge through the transformation of experience, learning-by-doing" (Armitage et al., 2008). Schusler et al. (2003) defines social learning as "learning that occurs when people engage one another, sharing diverse perspective and experiences to develop a common framework of understanding and basis for joint action." Yet other scholars focus on the multi-loop aspect of social learning that involves learning by changing actions without questioning assumptions (single-loop learning), learning that leads to reframing of the problem and guiding principles (double-loop learning), and learning that transforms the entire regime under which the assumptions about the system are made (triple-loop learning) (Armitage et al., 2008; Fabricius and Cundill, 2014; Pahl-Wostl, 2009).

The values of social learning can be found in both the process and its outcomes. For example, social learning could enhance relationships among stakeholders and increase satisfactions of stakeholders through the planning process, which could lead to increased adaptive capacity of a collaborative effort to solve complex socio-ecological problems (Gerlak and Heikkila, 2011; Pahl-Wostl et al., 2007a). Additionally, social learning could lead to outcomes (e.g., river basin management plans) that are more effective (Pahl-Wostl et al., 2007b). While examining case studies of river basin planning partnerships in Europe, Mostert et al. (2007) found that an important characteristic of social learning is the incorporation of diverse knowledge and points-of-view during deliberation and collaboration. Each stakeholder has different "frames" with which they perceive problems and develop different solutions. By recognizing these different frames, the stakeholders could develop a better understanding of the issues at hand and potentially develop innovative solutions (Mostert et al., 2007).

Social learning outcomes can be measured at both the individual and community level. Common learning outcomes at the individual stakeholder level include instrumental and relational learning (Benson et al., 2016; Brummel et al., 2010; Bull et al., 2008). Some scholars further differentiate instrumental learning into cognitive learning where changes occur in stakeholders' understanding of the social and ecological context, as well as learning about other stakeholders' points of view (Ernst, 2018; Siddiki et al., 2017), and technical learning where stakeholders obtain new skills applicable to the environmental problem at hand (Albert et al., 2012). Relational learning, sometimes referred to as communicative learning, pertains to what stakeholders have learned about each other's values and roles through collaboration and deliberation (Brummel et al., 2010; Muro and Jeffrey, 2008). An example of a relational learning outcome is development of new connections and professional network, as well as strengthening of existing interpersonal relationships (Koontz, 2014; Muro and Jeffrey, 2008). Another important relational outcome from social learning is increased trust among stakeholders (Mostert et al., 2007; Siddiki et al., 2017). At the community level, social learning could lead to collective actions such as implementation of management actions and policy change (Benson et al. 2016; Suškevičs et al. 2018).

The importance of social learning in natural resource management also prompted researchers to identify conditions that either foster or impede learning. Some factors that promote learning are related to the deliberation and collaboration processes. For example, setting ground rules that allow for transparency of the decision-making process and flexibility in including diverse opinions as well as democratic procedures for handling disagreements are considered key in fostering successful social learning (Ernst, 2019a; Gerlak and Heikkila, 2011; Pahl-Wostl et al., 2007a). While comparing cases of watershed planning in U.S. and Germany, Koontz (2014) found several factors influenced social learning outcome such as whether stakeholders were able to set meeting agenda ("process control"), participation was equal among stakeholders ("process equity"), the process included stakeholders with diverse viewpoints ("inclusiveness"), stakeholders have multiple opportunities to engage with each other over time ("extended engagement"), and opportunities existed for stakeholders to exchange information ("information exchange'). Effective leadership and availability of facilitators during the deliberative process has also been found to have positive effect on social learning outcomes (Mostert et al., 2007). On the other hand, factors such as lack of clarity for stakeholder roles and involvement, failure to include diverse stakeholders, lack of resources and adequate governance structure have been seen to impede social learning (Mostert et al., 2007).

Despite recent increase in studies on social learning in environmental governance and natural resource management, certain areas about social learning remains underexamined. Gerlak et al. (2019) reviewed studies about social learning and pointed out that there lacks a contiguous theoretical framework for analyzing social learning in environmental governance. Many concepts about social learning are disconnected, making comparisons across studies and cases challenging (Gerlak et al. 2019). Other knowledge gaps in social learning include whether social learning improves decision-making, the missing link between social learning and collective action, and whether social learning leads to behavioral and environmental change (Assuah and Sinclair, 2019; Cundill and Rodela, 2012).

Within the area of environmental governance and sustainability, social learning has been examined under various contexts. There have been extensive examinations of social learning in the context of watershed planning and management (Mostert et al. 2007; Pahl-Wostl et al. 2007; Koontz 2014). Brummel et al. (2010) investigated whether government-mandated local collaboration to develop wildfire plans in the U.S. produced intended learning outcomes. Leach et al. (2014) used surveys to identify evidence of social learning (i.e., belief change and knowledge acquisition) in marine aquaculture partnerships in the U.S. However, application of social learning concepts in the context of conservation and management of threatened species is lacking. Threatened and endangered species conservation can especially benefit from social learning, as there is often limited knowledge about the species and efforts to conserve the species and its habitat require collaboration among stakeholders with divergent perspectives. Further, endangered and threatened species conservation often relies on expert knowledge due to limited knowledge and empirical data about the species (Fitzgerald et al. 2021). Therefore, social learning among key stakeholders and species experts may contribute to effective conservation of endangered and threatened species.

In this study, we evaluate social learning in natural resource management, specifically in the context of threatened and endangered species conservation within a stakeholder group dedicated to conservation of an imperiled fish species in the southeastern U.S. We follow the definition of social learning by Gerlak et al.(2019b) as "processes that involve active deliberation and engagement by diverse actors in environmental governance, which can lead to new understanding or shared meaning". Additionally, we also aim to connect the outcomes of social learning to collective actions taken by stakeholders to demonstrate the value of social learning in environmental management. Specifically, our research questions are:

1) Has social learning occurred as an outcome of collaboration and deliberation among stakeholders? If so, what types of learning have occurred?
2) What factors act as facilitators or barriers to the social learning process?
3) Does social learning lead to collective actions that benefit the species or the environment?

Materials and methods

Study context

Fishes in the family Catostomidae, including suckers and redhorses, play important ecological roles and yet are much less known compared to their sportfish counterparts (Cooke et al., 2005). The limited knowledge on Catostomids could be attributed to that some species are difficult to identify and that some occur in habitats that are difficult to sample, thus making them challenging to study which impedes effective conservation and management of the species.

Conservation of suckers and redhorses can be further complicated by environmental threats they face, including hydropower dams that obstruct their migratory pathways to and from spawning grounds, water pollution from contaminants and sediment run-off in the rivers, and amounts of water released from dams that are not suitable for rearing young. Robust Redhorse (*Moxostoma robustum*) has received much attention after specimens were found in the Oconee River in Georgia in 1991 after approximately 100 years of not being observed in the wild. The "rediscovery" of the species occurred during a relicensing sampling event conducted by Georgia Department of Natural Resources personnel. Currently, the species occurs in the Altamaha River basin in Georgia, the Yadkin-Pee Dee River basin in North Carolina, and the Savannah-Santee River basin in South Carolina (Figure 4.1).

In the early 1990's, the Robust Redhorse in the Oconee River was the only known extant population at the time, therefore the species was perceived to be vulnerable to extinction. In lieu of listing the species under the Endangered Species Act, biologists and researchers formed the Robust Redhorse Conservation Committee in 1995 under a Memorandum of Understanding that was signed by federal agencies, state agencies, utilities, and NGOs[1]. According to the RRCC's policy document (2002), the short-term goals of the Committee include "establish refugial populations; locate other wild populations; determine population characteristics; and implement management and regulatory actions to maintain the existing known populations". The long-term goal of the Committee is to "establish or maintain at least six self-sustaining populations distributed within a significant portion of [Robust Redhorse's] historic range".

[1] The complete list of signatories of the original Memorandum of Understanding under which the RRCC is formed includes Georgia Department of Natural Resources, North Carolina Wildlife Resources Commission, South Carolina Department of Natural Resources, Georgia Power Company, Duke Power Company, Georgia Wildlife Federation, U.S. Fish and Wildlife Service, and Carolina Power and Light.

After the formation of the RRCC, a Candidate Conservation Agreement with Assurances (CCAA) was established between Georgia Power company and Georgia Department of Natural Resources, and the U.S. Fish and Wildlife Service with the goal of implementing conservation actions for Robust Redhorse in the Ocmulgee River within the Altamaha drainage to ensure sustainability of the population (U.S. Fish and Wildlife Service 2002). The CCAA outlined specific actions that USFWS, GA DNR and Georgia Power would implement to ensure sustainability of the population and the species, including reintroducing the species in the Ocmulgee River. The CCAA would last for 22 years which coincides with the duration of the Federal Energy Regulation Commission's license for Lloyd Shoals dam in the Ocmulgee River and is due for a renewal in 2023. Since the establishment of the RRCC, a population of Robust Redhorse was discovered in the Savannah River in 1997 and another was discovered in the Pee Dee River in 2000. Further management actions have been implemented in all river basins where Robust Redhorse is found to achieve RRCC's long term goal. Currently, Robust Redhorse has been petitioned to be considered for federal listing under the Endangered Species Act by the Center for Biological Diversity along with over 400 other species.

The RRCC holds annual meetings with representatives from signatory agencies/companies to provide updates on research, monitoring, and management activities, as well as discuss policy amendments when necessary. The annual meetings typically last for one and a half days except for 2020 and 2021 when meetings were held virtually and only lasted for one day. The RRCC is governed by the Executive Committee, which is responsible for the daily operations of the Committee, including leading the annual meetings and managing the Committee budget (Robust Redhorse Conservation Committee Policies 2002). Under the RRCC, there are different technical working groups (TWG), each responsible for implementing monitoring and management actions within specific basins, as well as TWGs on specific aspects of the Committee. For example, the IT TWG is responsible for maintaining RRCC's website (robustredhorse.com) which stores information, documents, and research output related to Robust Redhorse.

Data collection

Investigating social learning as a process and evaluating its outcomes require assessing participants' level of learning over time (Measham, 2013). Many social learning studies use a participant self-reporting approach to assess learning, which often involves researcher-designed survey instrument or semi-structured interviews for participants to assess their own learning (Ernst, 2019b). However, self-reporting methods alone may not be adequate in assessing social learning at the individual level because they often provide a snapshot of participants' perspective at a single point of time, usually after a participatory process (Ernst, 2019b). Therefore, participants may under- or overestimate their levels of learning and sometimes may "edit" their response when answering uncomfortable questions (Ernst, 2019b). Instead, ex post methods that take a longitudinal view at the learning process and factors that affect learning may be better suited for assessing changes in participants' attitudes, perceptions, and values prior to, during, and after engaging in a participatory process (Ernst, 2019b).

In this study, we used two primary data sources to assess social learning among RRCC members. First, we reviewed RRCC's official documents to gain a better understanding of the context under which the Committee was formed, as well as to assess what the Committee has learned together as a group. Second, we conducted semi-structured interviews with past and current RRCC members to assess learning at the individual level and identify factors that affected learning. The document review complements information gathered from interviews to situate learning at the group level as well as help identify collective group actions that resulted from social learning.

Document review

The documents we reviewed include the annual meeting summaries published by the RRCC on its website. During document review, we looked for evidence of learning by identifying what had been learned by the group through collaborative monitoring and research activities about Robust Redhorse, the threats faced by the species, as well as the ecosystem. We also identified any collective actions that the Committee implemented as a result of learning.

Semi-structured interviews

We conducted semi-structured interviews with RRCC members between January and March 2022. Prior to recruiting interview participants, we obtained a list of past and current RRCC members and their contact information from RRCC and emailed recruitment letters to those who have been or were involved with RRCC for more than 3 years. We chose 3 years as a cut-off for length of involvement because we wanted to exclude those who were relatively new to RRCC and thus may not demonstrate learning.

We conducted the interview either over the phone or on a virtual meeting platform. During the interviews, we followed a protocol with predeveloped questions (Appendix B) to guide the interview while allowing for flexibility for the participants to respond to the questions (Bernard, 2017; Newing, 2010). We collected audio recordings of the interviews and used an online transcription software (otter.ai) to convert the recordings into text, which was reviewed for accuracy by the researcher. Study procedures were approved by UGA's Institutional Review Board (PROJECT00001511) before the recruitment of interview participants began.

Interview data analysis

We conducted qualitative content analysis of interview transcripts by assigning "codes" to texts summarizing participant responses relevant to answering our research questions. We then organized and combined codes into categories to identify common patterns among responses. We used an inductive coding approach where a codebook was not established prior to analyzing interview responses (Saldaña, 2014). Instead, we coded respondent's experiences as a mixture of "in vivo", "versus", "descriptive", and "process" codes while reviewing the interview transcripts (Saldaña, 2021). After codes are assigned to data, we then group similar codes into categories to identify themes that emerge from across interview responses. All coding was conducted in MaxQDA 2020 (VERBI 2021).

Results

We reviewed RRCC annual meeting summaries from years 1995-2001 and 2003-2017. These annual reports document updates provided by RRCC members on research, monitoring, and management activities within the previous year. The reports also sometimes document discussions among members about information presented during the meeting as well as planning activities for the following year. We interviewed 20 RRCC members between January and March 2022, including 11 from state natural resource agencies, 3 from federal agencies, 4 from utilities, and 2 from academic institutions working in the southeastern U.S. The length of involvement with the RRCC ranged from 5 to 28 years. Interviews lasted between 24 and 75 minutes. The roles of RRCC members vary in nature, some have been routinely involved by attending annual meetings as well as technical working group meetings. Some have also held leadership positions on the Executive Committee of the RRCC, while others play support roles in monitoring activities or attend meetings but are not otherwise involved in research or management activities. Below we present and discuss the results from the qualitative data analysis. A graphical depiction of our findings is presented in Figure 4.2.

Social learning outcomes

Instrumental learning

A common social learning outcome is instrumental learning in which stakeholders gain new skills and knowledge through collaboration and deliberation (Brummel et al., 2010; Koontz, 2014; Siddiki et al., 2017). Our interviews revealed that instrumental learning occurred at both individual and Committee levels. On the individual level, most respondents indicated that they have gained knowledge about Robust Redhorse and the environmental issues negatively affecting their persistence. Several respondents, including both old and new RRCC members, stated that they had little or no knowledge of Robust Redhorse or the river systems in which they occur prior to joining the RRCC and have since gained substantial knowledge. However, a few respondents indicated that they already had knowledge of Robust Redhorse and its habitat and ecosystem prior to joining the Committee due to exposure to the species from their educational background or their professional activities. Even so, the respondents in our study who were already familiar with Robust Redhorse prior to joining the Committee still expressed that they gained a deeper understanding and appreciation for the challenges and complexity associated with managing a fish species in large river systems after their involvement with the Committee. As one respondent stated:

> *"Prior to joining [RRCC], like I said, I knew about Robust Redhorse just because if you're in the fisheries program at [Academic2] you can't not hear about it… [I] have since learned there's a whole lot of factors at play. You know, as we've learned more about where the juveniles actually are, that's sort of opened up the wider river length*

conversation to like, you start getting down into salinity, and you realize they're utilizing these whole rivers as opposed to just an area where they might have been seen spawning." (Utilities personnel)

Another respondent marveled at what he has learned about the intricacy of the system in which Robust Redhorse is found and how focusing on a single species can help researchers understand how anthropogenic activities affect the ecosystem:

"I have a greater appreciation for how species that are specialized for things like benthic survival can still contribute on a very large scale to these ecosystems and how they are impacted themselves by basically every change that humans make to the environment. So what it's kind of opened my eyes to is that these systems are even more intricate than I would have imagined, even after my years of education. And that we really do have to focus sometimes on individual species to understand the ecosystem as a whole." (State agency personnel)

Several respondents claimed that they have gained technical skills related to fisheries management since joining the RRCC, including learning about new population monitoring techniques, genetic considerations for stocking the populations, and procedures involved in spawning and rearing Robust Redhorse in captivity. Committee subgroups, especially newly established TWGs, also learned from the body of knowledge that the Committee has accumulated since its establishment. For example, the Yadkin-Pee Dee TWG was formed under the Committee after Robust Redhorse was discovered in the Pee Dee River in 2000. According to one TWG member, the group initially needed more guidance from other more experienced

TWGs on monitoring the population in the basin. Over time, the Yadkin-Pee Dee TWG has become more "*mature*" and needs less assistance from the Committee.

At the Committee level, instrumental learning is evidenced by what is learned about Robust Redhorse and its habitat preferences by the Committee through collaborative research and monitoring activities. Both interviews and annual meeting summaries demonstrated that the Committee as a whole has gained substantial knowledge regarding the species' natural history and biology and has co-developed and improved upon aquaculture and sampling techniques overtime. A recent example is a collaborative effort among RRCC member organizations to place sonic tracking devices in adult Robust Redhorse in the Savannah River. This tracking study was initiated in 2018 and, to date, has revealed seasonal movement patterns of fish and furthered the Committee's understanding of habitat usage of Robust Redhorse within the system.

Relational learning

Many interviewees expressed that they have found that others on the Committee share similar values as they do, and that everyone is "*working towards a common goal*", which helps unite the group and make progress:

> *"I think our common bond is that we all share a natural resources background. And so because of that, we probably all initially shared, you know, our own love and respect for our natural resources, which took everybody down that professional path to begin with. And I think that has been the bond that has kept this group together and moving forward throughout the whole time." (Utilities personnel)*

Some RRCC members stated not only have they learned about other members personal values related to conserving Robust Redhorse, but they have also come to recognize the distinction between either their own or other members' personal values and the values of the organizations they represent. This phenomenon is more prominent in the utilities sector:

> *"I think the industry groups, obviously, our operations have to drive everything we do. So those of us that are trained in this field, sort of get the conservation for the sake of conservation ethic. That doesn't necessarily translate to shareholders all the time… the personal views don't always align perfectly with who's paying your paycheck. But when you come to that table, you also, you know, you're representing it, for the most part, you're representing a job." (Utilities personnel)*

> *"I think everyone involved in the private sector as individuals are, they're really committed. And they're committed to the conservation, committed to the species. But they're limited by their mission of their company, right, or whatever organization they're working for. We're all limited by our mission. (State agency personnel)*

Evidence also suggests that RRCC members have gained trust from one another over time through continuous involvement. Interviewees who have been involved with RRCC since the early years indicated that early meetings were very contentious, because the Robust Redhorse found in the Oconee River were thought to be the only extant population of the species, and that the members thought they were what "*stands between the fish and extinction*" and nobody wanted to "*do the wrong thing*". The tension surrounding the high stakes of the conservation effort resulted in meetings where "*things almost came to blows a couple of times*", as one respondent recalls. With help from outside facilitators and continued deliberation which led to agreement among members regarding the definition of terms used by different stakeholders, the stakeholders were able to move forward and became more comfortable working with one another and respect each other's input. As one respondent stated:

> *"Now, if you look at it, just from my experience, definitely people that argued about things 20 years ago are now buddies, and very comfortable working with each other, which is really good." (State agency personnel)*

Other indicators of trust included when respondents expressed that they view the stakeholders from other organizations as coming to the table in "*good faith*", and that everyone wants to "*do the right thing*".

Being involved with RRCC has also allowed stakeholders to make new connections, as well as strengthen existing interpersonal relationships. Several respondents claimed that their professional network has expanded as a result of joining the RRCC and collaborating with other RRCC members. They also indicated that they would not have connected with some of the members if they had not collaborated on recovery efforts for Robust Redhorse. The professional connections made through the RRCC have multiple beneficial outcomes that extend beyond RRCC: 1) they allow stakeholders to feel comfortable reaching out to each other to request their expertise regarding issues not related to Robust Redhorse; 2) they make for easier collaborations outside of RRCC because of the pre-existing professional relationships; and 3) they help transcend spatial boundaries when managing resources shared between states. For example, one state agency employee said knowing personnel from other state natural resource agencies allowed her to reach out to them more easily and ask for their input when reviewing impacts of water withdrawals from a water body shared by both states.

Factors affecting learning

Diversity of stakeholders

The stakeholder group of RRCC includes organizations such as federal agencies, state natural resource agencies, utilities, and non-governmental organizations. The diversity of stakeholders allows the Committee to approach the problem from different points of view and "*learn about diverse ways of thinking*", as one respondent stated. Aside from differences in type of organizations involved, RRCC stakeholders also consist of organizations from all three states where the species occurs. Spatial misfit is an important challenge faced by stakeholders managing natural resources shared across spatial boundaries (Young and Gasser, 2002). Having natural resource agencies from states that cover Robust Redhorse's entire range helps facilitate coordination among states when implementing conservation actions.

The RRCC also consists of members with different levels of experience and lengths of involvement with the Committee. Some interviewees were founding members of the Committee, indicating more than 2 decades of involvement, whereas others became involved within the last 5-6 years. The different lengths of involvement are beneficial for the learning process of RRCC, as the older members offer "*institutional knowledge*" and expertise and can help newer members navigate the challenges they are facing with Robust Redhorse recovery efforts. On the other hand, newer members offer fresh perspectives and bring different skillsets to the table that could help the Committee challenge its long-standing assumptions regarding issues such as species habitat needs and ecosystem dynamics. One interviewee expressed his appreciation of another RRCC member who challenged an assumption long held by the Committee regarding the bottleneck in the recovery of Robust Redhorse populations:

"It was interesting, [name]… he's a newcomer to the group, and it's just interesting to see things through outsider eyes. He was really questioning, maybe the limiting factor is juvenile habitat somewhere downstream; it's not spawning habitat. It's just everybody kind of shrugged and said 'we assume it's spawning habitat we don't know. Next question.'" (Academia member)

Frequent and sustained engagement

Social learning is a continuous process that requires frequent and sustained engagement among stakeholders. For RRCC, one form of engagement among members is the Committee-wide meeting held every year. The annual meetings serve several purposes for the RRCC, which promotes social learning among members. First, the meetings provide a space and time dedicated solely to Robust Redhorse conservation. Some respondents indicated that the meetings are helpful for them to focus on a single issue without distractions from their other duties. Second, at each meeting, stakeholders not only update the Committee on progress made to-date on previously set research and management goals, they also share goals for the upcoming year, which provides a form of accountability among members. Third, the annual meetings help stimulate idea exchange, as formal progress updates are often followed by discussions where members can ask clarifying questions of the presenters and offer potential solutions for challenges faced by specific stakeholders. Lastly, the informal interactions during the annual meetings such as breaks between presentations and the evening social encourage relationship building and further idea exchange by allowing members to have one-on-one discussion on topics that they may not feel comfortable bringing up during the formal deliberations, as one respondent pointed out:

"When in a formal setting, folks might feel inclined to fly their agency's banner. So even if they have a personal opinion that's different from what the company position is in public, they have to fly the company's flag. But if you're having a beer with somebody, and really it's just the two of you, you might get a better handle of what they feel, A, and B, the challenges they face in voicing there publicly. But by conveying that information to you privately, it still can inform how you do the work you do, or share information in such a way that frees them to support it without contradicting the company flag." (Federal agency personnel)

Additionally, as RRCC members often collaborate with one another on monitoring and research activities, members also communicate outside of the annual meetings to coordinate sampling efforts, develop funding applications, and provide periodic updates.

3.2.3 Quality of information exchange and deliberations

In general, respondents think that the presentations providing progress updates on research and management activities are of good quality and the information presented is easily understandable. However, some members think the "*cookie cutter*" presentations from year to year sometimes failed to connect back to RRCC's overall goals.

"It's just seeing the forest for the trees and keeping the conversation forest-focused, is just, that's the challenge, that that would be the growth angle I think for any conversation we have." (Academia member)

With regard to inclusivity of diverse opinions, respondents think that their opinions are taken seriously during meeting discussions. When asked how the Committee made them feel that their opinions are heard and valued, one respondent said that *"the reason you know that they're* *valued is to generate more discussion. I don't think they're ever somewhat summarily dismissed or dismissed without good cause."* Others stated that they perceive the Committee members as "*respectful*" of everyone's opinions and are "*thoughtful*" when answering questions that come up during the meetings. However, while many recognized the diversity of the stakeholder group and different ways of thinking as a strength for the RRCC, some express frustration when "*dichotomy of beliefs*" sometimes stymie progress and decision-making because the majority could not come to a consensus about a clear path forward.

Respondents also have an overall positive response when asked how the Committee handles disagreements when they arise. Many interviewees recall that the Committee strives to build consensus among members when making decisions regarding monitoring, research, or management actions, although consensus sometimes cannot be reached. When disagreements arise, the Committee can often work through them constructively, as one stated, *"the best thing about this group is that we didn't work in that space of conflict*. The RRCC policies (2002) outlines a voting process the Committee may employ in making decisions, although whether the process is used in every decision-making context is unclear. However, some members stated that they have found to expressing opinions difficult at times because they view RRCC as a "*tight-knit*" group with some members having been involved since the beginning, and expressing their opinions as a new member could be intimidating. Further, the same respondent who praised the benefits of the Committee members being "*buddies*" also cautioned the downside by explaining "*if you're with all your buddies, they're not going to challenge you*", indicating the possibility of developing group think among Committee members over time which may stifle innovation and challenging of assumptions.

Format of engagement

The COVID-19 pandemic posed challenges to engagement by limiting in-person interactions among RRCC members. In 2020 and 2021, RRCC annual meetings were held virtually, and several interviewees lamented on the reduced engagement from meeting participants. As aforementioned, informal conversations outside of the scheduled presentations and deliberations at annual meetings are crucial for idea exchange and relationship building, which is lost in the virtual format:

> *"[V]irtual meetings are so cut and dry. You can't have those interactions, those one-on-one, sidebar conversations. You can't talk about ideas over a beer to social, which, in my opinion, all these meetings, that's where the best ideas happen." (State agency personnel)*

RRCC members also engage with each other using other formats of communication. Aside from annual meetings, many respondents stated that they communicate with each other via email, and occasionally would connect at other professional meetings.

Available resources

Natural resource managers often work under the constraint of available funding and manpower to conduct monitoring, research, and management activities. Funding for managing non-game fishes such as Robust Redhorse are often limited compared to managing sportfish. When asked about opportunities and challenges associated with conserving Robust Redhorse, many respondents cited funding as a resource and constraint. Interestingly, members had disparate perceptions regarding availability of funding for RRCC to conduct research and management activities in that some perceive funding to be sufficient while others think funding is limited. Further, interviews revealed that whether the Committee uses its funding effectively may be more important than availability of funding. One respondent stated that she felt that the earlier funding from the Committee supported research that were "*low hanging fruits*", and that the research didn't "*get at the questions that mattered*" which hindered opportunities to learn and manage the species effectively.

Collective actions and policy change

In the case of Robust Redhorse Conservation Committee, the social learning process and outcomes have led to some small-scale policy changes. For example, at the Committee level, the early contentious deliberations led the Committee to develop policies for defining short-term and long-term goals for the Committee, as well as reducing linguistic uncertainty among stakeholders. For example, the policies defined criteria for conducting field surveys for Robust Redhorse such as amount of time spent during survey and river miles covered ("Robust Redhorse Conservation Committee Policies," 2002). Additionally, the Committee also developed stocking policies for population augmentation efforts in the Pee Dee evolutionary significant unit. Other collective actions taken by RRCC members include collaborative monitoring efforts, implementation of management actions such as spawning and rearing Robust Redhorse in captivity, population augmentation (stocking), and habitat improvement. RRCC also implemented management actions directed at improving habitats for Robust Redhorse. For example, changes to amount and timing of water release by hydropower dams were implemented by Georgia Power in the Oconee River after research identified water flow regime that would create ideal rearing conditions for larvae Robust Redhorse during the rearing season. However, whether the water flow changes benefited Robust Redhorse populations in the river remains unclear.

At the organizational level, the strengthened connections and trust among stakeholder groups have resulted in collective actions outside of the RRCC as well. For example, Georgia Department of Natural Resources, U.S. Fish and Wildlife Service, and Georgia Power Company entered a Candidate Conservation Agreement with Assurances to conserve the mollusk species in Georgia, an agreement some members claimed as a result of the positive relationship the partners built through collaborating on the Robust Redhorse CCAA.

Discussion

Despite the importance of social learning in environmental governance and natural resource conservation, case studies in social learning in threatened and endangered species conservation are rare. In our study, we found that both instrumental and relational learning occurred within the RRCC in the context of Robust Redhorse conservation. More specifically, RRCC members have gained new knowledge about Robust Redhorse and the ecosystem in which it occurs as well as issues facing the species and the ecosystem in which the species occurs. Increased trust among members and expanded professional networks were also evident through analysis of interview data. We also found that several factors affected the learning process, including factors related to the group characteristics such as diversity of stakeholders, group dynamics, and quality of information exchange and deliberations, as well as external factors such as availability of resources and format of deliberations (in-person vs. virtual). Lastly, social learning led to not only collective actions taken by RRCC members aimed at recovery of Robust Redhorse and its habitat, but also collaborations beyond Robust Redhorse conservation. Below we discuss the major findings from the study.

Social learning outcomes

Given the RRCC is a collaborative partnership with a 27-year history, perhaps not surprisingly, the collaborative efforts and deliberations that have taken place resulted in substantial instrumental learning at both the individual and Committee level. In the early years following the "rediscovery" of the species, little was known about it, and collaborative research and monitoring were critical to social learning. By identifying knowledge gaps and research needs in the beginning, the Committee was able to contribute to the collective body of knowledge on many aspects of the species' natural history and help refine management techniques such as aquaculture and genetic protocols for reintroduction efforts. Instrumental learning or cognitive gain has been found in many social learning contexts, including watershed planning (Koontz, 2014), community forest management (Assuah and Sinclair, 2019), flood risk management (Benson et al., 2016), and marine aquaculture policy (Siddiki et al., 2017). However, some authors found instrumental learning to be limited in cases where stakeholders had previous knowledge about the natural resource or environmental problem before entering a collaborative or participatory partnership (Benson et al., 2016; Brummel et al., 2010). Our study found some evidence of limited instrumental learning in members who had previous knowledge about Robust Redhorse and fisheries management in general prior to joining the RRCC. This could be explained by the fact that most RRCC members have education and professional background in fisheries biology and management, and the knowledge and skills they possessed were transferrable to Robust Redhorse conservation and management. Nevertheless, most of the respondents in our interviews, regardless of previous levels of knowledge, indicated that they learned more about Robust Redhorse and the dynamics and intricacy of watershed systems as whole after joining the Committee.

Trust building, network development, and learning about other's worldview are often cited as relational outcomes of social learning (Benson et al., 2016; Koontz, 2014). Relational learning among RRCC members is demonstrated by increased trust among RRCC members and comfort level collaborating with one another. Many interviewees stated that their professional network expanded since joining the RRCC and some of the connections they have made would not have happened without being involved with the Committee. The newly developed connections and existing connections that are strengthened by deliberation and collaboration among members have led to improved communication outside of RRCC, with some members claiming that they feel comfortable reaching out to other RRCC members about other projects or issues that are not related to the Committee.

Stakeholder dynamics and learning

The frequent and continuous engagement of RRCC stakeholders likely facilitated social learning among members. Researchers of social learning have cited "extended engagement" as a factor that facilitates social learning (Koontz, 2014; Leach et al., 2014; Schusler et al., 2003). Aside from annual meetings where members provide research and management progress updates, RRCC members regularly communicate with each other to coordinate field research and monitoring, writing grant applications for additional funding, and discuss specific issues such as database management and watershed-specific activities. Furthermore, many RRCC members have been involved with the Committee since its early years, and some members have continued to attend meetings beyond their professional retirement.

Diversity in background and worldview within the stakeholder groups can act as a double-edged sword for social learning. The respondents in our study generally praised the institutional diversity of RRCC members, citing the wide array of background and sectors that are represented on the Committee. Additionally, diversity also exist in lengths of involvement of members, some having been involved since the Committee was established; others are relatively new. Siddiki et al. (2017) stated that "diversity exposes participants to new information and new perspectives" while, "diversity can also be threatening, leading stakeholders to react to new information defensively, which impedes knowledge assimilation and belief change and potentially thwarts collective action…" In the case of RRCC, stakeholder diversity has promoted learning, but the diverse opinions that are firmly held by some members can sometime impede decision-making and action.

Quality of interactions and learning

Social learning scholars have found that inclusivity of deliberative processes creates conditions that promote social learning (Koontz, 2014)). In the case of RRCC, members are generally positive about how inclusive the Committee is of different stakeholders' views and beliefs. This is evidenced by the fact that members, in general, feel comfortable expressing their opinions during meeting discussions and feel that their opinions are taken seriously by the group instead of being dismissed without cause. Conflicts, when handled appropriately, can also facilitate learning. Several interviewees in our study stated that meetings among RRCC members during the early years were contentious, which led to the Committee developing policies that reduce linguistic uncertainty and make sure everyone's on the same page. The policies provide structure and transparency to the RRCC decision-making process, which lends legitimacy to the process itself and of the decision and action (Koontz et al. 2014 and Ernst 2019).

In our study, we found that presence of facilitators may promote learning regardless which stage of the deliberation process the stakeholder group is in. As aforementioned, RRCC meetings in the early years were contentious, and the presence of facilitators helped keep stakeholders engaged and moving forward instead of abandoning the process despite differences in opinions. RRCC meetings in recent years have not had facilitators present, as contention is rare. However, one interviewee in our study suggested that the group could benefit from a third-party facilitator who is not invested in the problem to help move things along and help the group make decisions, as members sometime can be overwhelmed with uncertainty or unable to resolve differences in beliefs to make decisions.

Aside from quality of formal deliberations, informal discussions at meetings are also essential for idea exchange and relationship building. The informal socials and breaks between formal presentations provide additional space for RRCC members to engage with one another on a one-on-one basis and learn more about each other's values and perspectives. Additionally, informal discussions can provide an alternative space for members to voice opinions that they may feel comfortable expressing in a formal setting. These opportunities were largely lost in the virtual meeting format that the RRCC used during the COVID-19 pandemic.

The need to challenge assumptions

Our findings demonstrate the importance of challenging assumptions in social learning. Whereas the RRCC had initial momentum and produced a new knowledge about the species, progress appears to have slowed in recent years. Indeed, some members view the progress of the Committee to date as merely slowing the decline of the species, and progress towards achieving the Committee's long-term goal appears to be "*stagnant*" currently. Additionally, some members described the progress updates at annual meetings to be "*cookie cutter*" and cited the need for innovation. Further, one respondent observed that the fact that the RRCC members are comfortable collaborating with each other sometimes means they do not challenge each other's opinions. This indicates that while increase in trust and comfort level among RRCC members is beneficial to the collaborative effort among actors, too much social cohesion could actually impede learning. While reviewing literature on social learning in social-ecological systems, Suškevičs et al. (2018) found that social cohesion may "prevent learning by fostering group thinking and closure". Therefore, to continue fostering alternative framings as well as innovative solutions, continuous effort needs to be invested by the group in reflecting on current framings of the management problem, as well as questioning assumptions the group has about the species and issues surrounding their recovery.

From learning to acting

Social learning can sometimes lead to collective actions taken by a group of stakeholders towards solving environmental problems (Assuah and Sinclair, 2019; Cundill and Rodela, 2012). In the context of Robust Redhorse conservation, RRCC members have taken collective actions in the form of management actions directed at helping Robust Redhorse populations recover. These management actions include introducing new populations within the species' historic range or augmenting existing wild populations by stocking juvenile fish, improving spawning habitat by adjusting water flow regimes and depositing gravel substrate in the Oconee River as well as stabilizing riverbanks in the Ocmulgee River in GA to reduce sedimentation in the river. However, to date, there is limited evidence that collective actions taken by RRCC stakeholders have improved long-term viability of the species. In fact, when asked about their perception of the progress that RRCC has made towards achieving its goals, some respondents in our study expressed that the Committee appears to have merely slowed the decline of the species, and they have reservations about whether the Committee will ultimately achieve its goal of establishing self-sustaining populations. One reason for the lack of evidence of visible environmental improvements could be that Robust Redhorse is a long-lived species where individuals do not reach maturity until 4-5 years old, and the longest living individual ever recorded was 27 years old (Robust Redhorse Conservation Committee). As such, management actions aiming to help increase population recruitment and establishing self-sustaining populations may take a long time to see results.

Evidence suggests that social learning among RRCC members not only spurred collective actions related to Robust Redhorse conservation, but also other conservation collaborations as well. The Candidate Conservation Agreement with Assurances for mollusks in Georgia is a notable example of collaborations among RRCC stakeholders that is unrelated to Robust Redhorse. Therefore, outcomes from one social learning context can be transferrable and could foster collaborations among similar actors in other environmental contexts.

Social learning and adaptive management

Adaptive management was first made popular by Holling (1978) and Walters (1986) as a natural resource management approach that focuses on experimenting and learning from newly emerged information. As learning is an essential component of adaptive management, some scholars have examined the role of social learning in adaptive management. For example, Cundill et al. (2012) stated that "[w]hereas adaptive management aims to test management interventions amid uncertainty, social-learning approaches additionally aim to explore the worldviews that inform management interventions. Underlying this process is the recognition not only of imperfect knowledge, but also of socially constructed values, knowledge, and aspirations." They further encouraged natural resource researchers and managers to engage in soft systems thinking where, instead of "considering the external world as the system that can be engineered", think of it as "observer's interaction with the complex real world" (Cundill et al., 2012). The soft systems approach that focuses on social learning better align with the reality of adaptive management of natural resources, as decision-making rarely exists in a vacuum uninfluenced by stakeholder values and worldviews. The RRCC is currently developing an adaptive management framework to help achieve its goals. Our findings suggest that social learning has occurred within the RRCC and that the Committee fosters conditions that promote social learning which can be incorporated in the adaptive management process. On the other hand, engaging in adaptive management can sometimes motivate stakeholders to develop partnerships and social structures required for an AM project to succeed (Moore et al. 2020), thereby creating conditions that could foster social learning.

Conclusion

In this study, we assessed level of social learning among stakeholders of the Robust Redhorse Conservation Committee, a collaborative partnership aiming to achieve recovery of Robust Redhorse populations in its range. Based on analysis of annual meeting summaries and semi-structured interviews with members, we found several lines of evidence demonstrating social learning has occurred among RRCC members which led to learning outcomes at both the individual and group level. We also found that factors such as group dynamics, actor diversity, and quality of interactions could affect social learning in this context. Lastly, we demonstrated that social learning outcomes in the case of RRCC can also be linked to collective actions aimed at helping Robust Redhorse populations recover as well as other collaborations outside of RRCC involving similar actors. Social learning has gained much attention as a mechanism to increase adaptive capacity of stakeholders in environmental governance. Gaining a deeper understanding of social learning, especially conditions that promote learning among key stakeholders and experts, could lead to effective endangered and threatened species conservation. The findings from our study will contribute to the social learning literature by demonstrating its benefits and challenges in species conservation, which could provide as an example for conservation practitioners who wish to adopt a similar approach used by the RRCC for conservation of other imperiled species in the future.

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Table 4.1. Definition of terms related to social learning. * Indicates types of learning examined in this paper.

Term	Definition	Source	Examples from RRCC
Social learning*	"Processes that involve active deliberation and engagement by diverse actors in environmental governance, which can lead to new understanding or shared meaning"	Gerlak et al. (2019a)	Since the establishment of RRCC, members have engaged with one another through collaborative research, monitoring, and management activities, as well as regular meetings to provide progress updates and identify next steps in achieving conservation goals.
Transformative learning	"A reflective process that enables an individual's perceptions and consciousness to be altered"	Muro and Jeffrey (2008)	NA
Experiential learning	"A process of creating knowledge through the transformation of experience, learning-by-doing"	Armitage et al. (2008)	NA
Instrumental learning*	"Gaining new skills and information related to the substance of an issue"	Brummel et al. (2010)	RRCC members have gained knowledge about Robust Redhorse and the ecosystem in which it occurs through collaborating on monitoring, research, and management activities
Relational learning*	Trust building, network expansion or strengthening, and group agreement	Koontz et al. (2014)	RRCC members have learned more about each other's values and priorities in the context of Robust Redhorse conservation. Some members also claim that their professional networks have expanded since joining the Committee.
Single-loop learning	"Refinement of actions to improve performance without changing guiding assumptions and calling into question established routines."	Pahl-Wostl (2009)	NA
Double-loop learning	"Change in the frame of reference and the calling into question of guiding assumptions."	Pahl-Wostl (2009)	NA

Triple-loop learning	"Transformation of the structural context and factors that determine the frame of reference."	Pahl-Wostl (2009)	NA

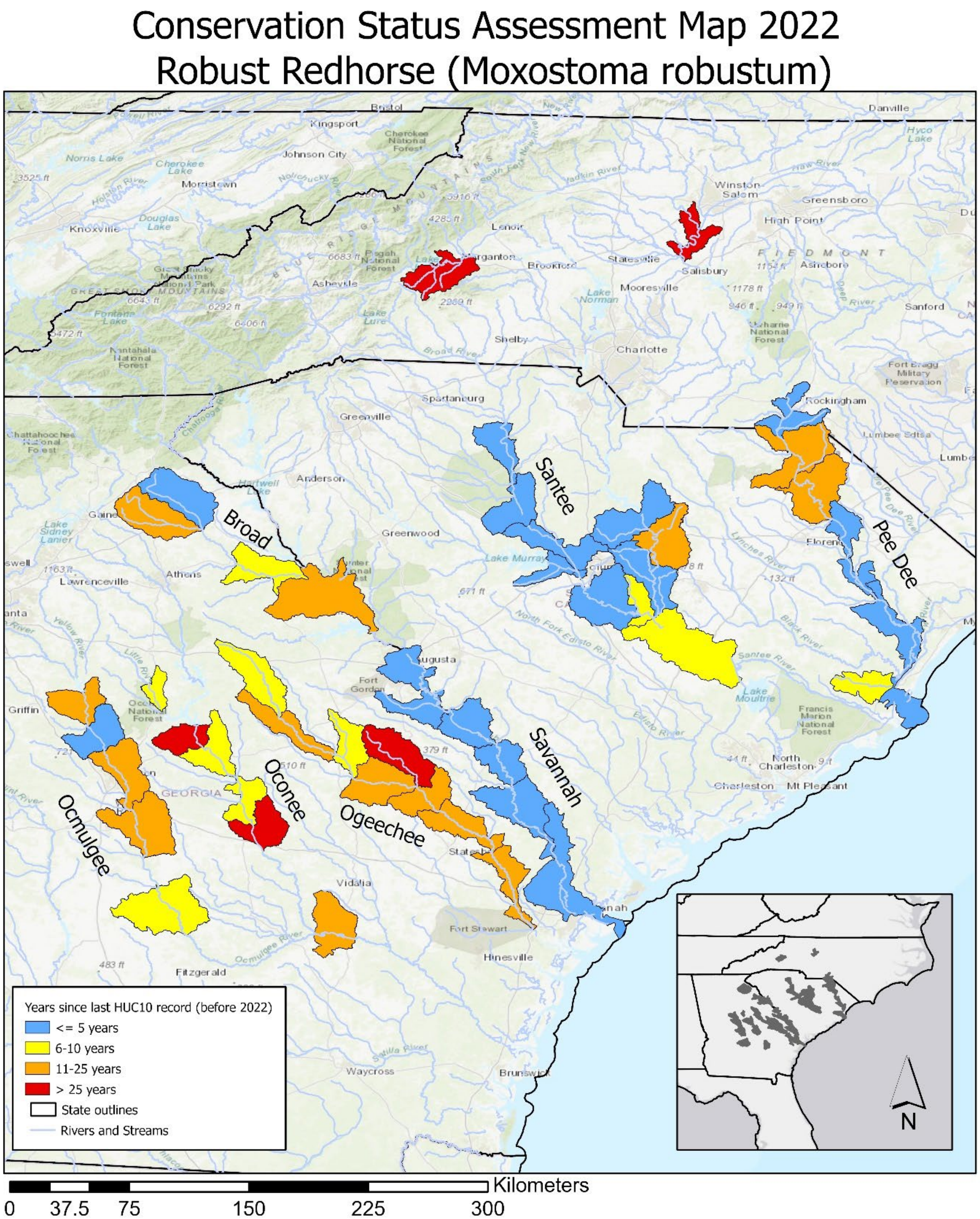

Figure 4.1. Current (2022) range map of extant Robust Redhorse (*Moxostoma robustum*) populations within its range. Map produced by Georgia Department of Natural Resources.

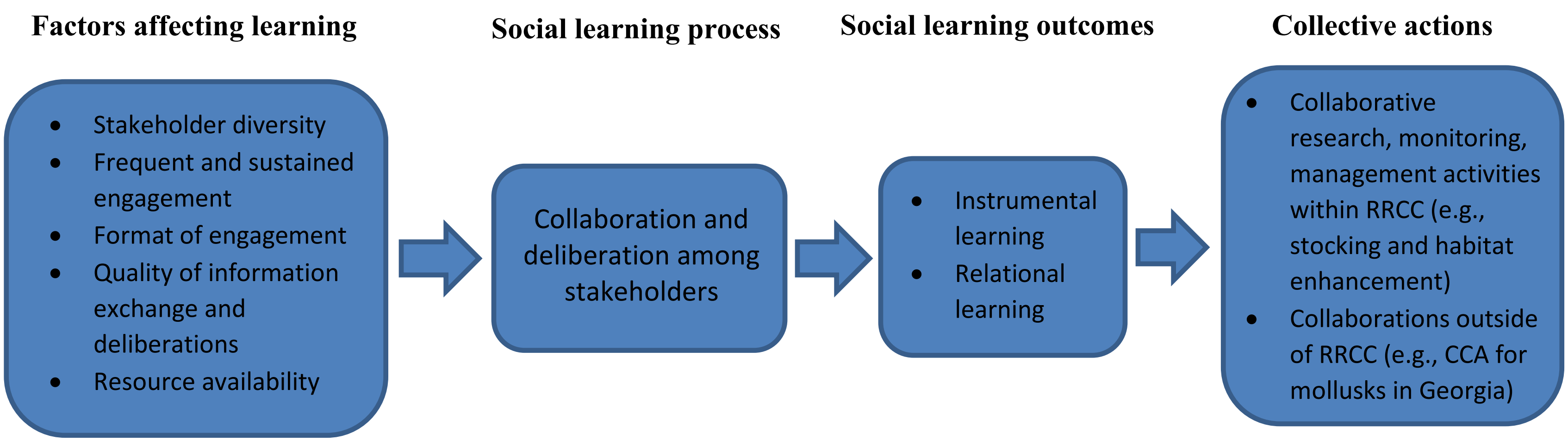

Figure 4.2. Graphical depiction of the social learning process and outcomes in the context of Robust Redhorse conservation based on semi-structured interviews with RRCC members and review of annual meeting summaries.

CHAPTER 5

CONCLUSIONS

This dissertation contributes to conservation of rare and imperiled fish in the family Catostomidae in several ways: 1) we modeled existing data collected from Sicklefin Redhorse and Robust Redhorse populations to estimate parameters that could inform management and conservation of the species, 2) working with members of the Robust Redhorse Conservation Committee (RRCC), we facilitated a decision-making process for evaluating management alternatives for Robust Redhorse at the level of defined Evolutionary Significant Units, working towards development of an adaptive management framework for the stakeholders to apply in the future, and 3) we helped elucidate social learning that has occurred within the RRCC since the collaborative partnership started and factors affecting learning, which could help improve future learning outcomes and decision-making processes. Both quantitative and qualitative approaches were used in this research to provide a more holistic view of the process, opportunities, and challenges facing conservation of imperiled fish species.

SUMMARY OF FINDINGS

Population dynamics of Catostomid fishes

Implementation of management actions for species conservation is best guided by available knowledge about the species and its populations, and conservation efforts can be hindered by unknowns about key demographic processes – such as survival and recruitment rates – as well as overall abundance. The findings from this dissertation helped fill existing knowledge gaps in population parameters of Sicklefin Redhorse and Robust Redhorse to better inform their conservation. Specifically, the Jolly-Seber population model in Chapter 2 provided estimates of parameters and abundance states for the population of adult Sicklefin Redhorse in Brasstown Creek, GA, including annual apparent survival probabilities, annual recruitment of individuals into the spawning population, and annual population size. The difficulty to observe rare and imperiled fishes could also impede managers' ability to gain a better understanding of population status. Therefore, to help biologists better plan monitoring efforts for Sicklefin Redhorse, we estimated detection probability by sampling gear type – fyke net and PIT antenna, thereby demonstrating the efficacy of both gears. In Chapter 3, we used a multistate model to analyze capture-mark-recapture data obtained survival probabilities for different life stages of the Robust Redhorse populations in the Pee Dee River and Savannah River . The estimates provided stage-specific (i.e., juvenile, young adult, and old adult) annual apparent survival probabilities and annual detection probabilities. The estimated adult survival probabilities for Sicklefin Redhorse and Robust Redhorse were relatively high, which are similar to estimates for other long-lived Catostomids. Having a better understanding of stage-specific survival probabilities is helpful in population viability analysis for a species under different scenarios, as each scenario may affect each life-stage of a population in different ways.

Conservation decision making for imperiled fish species

Structured decision making offers a framework for conservation practitioners to make management decisions that are defensible and encourage stakeholder buy-in. In Chapter 3, we guided the stakeholders of the RRCC through an SDM process while facilitating expert-elicitation workshops where we helped the group develop the problem statement, management objectives, alternative scenarios, and performance metrics for evaluating management scenarios. We then conducted a population viability analysis to project Robust Redhorse populations into the future to help build a framework for making management decisions and implement adaptive management in the future. The parameter input of the PVA was informed by both model-estimated values when available and expert-elicited values. The PVA demonstrated that management scenarios that include improvements to spawning and rearing habitats in combination with stocking efforts performed better compared to those that only included stocking efforts alone. Additionally, anticipated climate change induced environmental changes, such as increasing water temperature, may negatively affect populations by reducing recruitment.

Adaptive management in species conservation involves recurrent decisions that are updated based on newly emerged information by monitoring responses to management actions. Adaptive management could help managers reduce uncertainty about the species biology and/or the system. Much uncertainty surrounds management of Robust Redhorse, including factors affecting age-0 and juvenile fish survival. Given that many management actions attempt to influence these life stages, shedding light on how early life stages respond to system perturbations is essential. Therefore, in Chapter 3, we also laid out potential steps for an adaptive management framework for the conservation of Robust Redhorse populations, including identifying important uncertainties that stakeholders could aim to address and potential recurrent decisions that need to be made during the iterative process.

Role of learning in conservation of imperiled fish species

Social learning has gained much attention as a mechanism to increase adaptive capacity of stakeholders in environmental governance. However, little is currently known about its role in endangered and threatened species conservation. Given that learning is a crucial element in the adaptive management process and that the RRCC is working towards developing an adaptive management framework for recovery of Robust Redhorse populations, we set out to examine

RRCC's capacity to learn as a group via collaboration and deliberation. In Chapter 4, we assessed social learning among stakeholders of the RRCC as well as identifying factors that affected the learning process and outcomes. Based on analysis of annual meeting summaries and semi-structured interviews with members, we found several learning outcomes indicating social learning occurred within the RRCC since its establishment. For example, the results demonstrated that substantial knowledge about Robust Redhorse biology, natural history and factors affecting their populations has been gained by the group through collaborative research and monitoring efforts (i.e., instrumental learning). Additionally, many members indicated that they have learned more about other members' values and points of view, and that their professional networks have expanded since joining the RRCC (i.e., relational learning). We also found that factors such as group dynamics, actor diversity and quality of interactions are important factors that affect social learning within the RRCC. Social learning outcomes in the case of RRCC can also be linked to collective actions aimed at helping Robust Redhorse populations recover, such as collaborative monitoring efforts and implementation of management actions such as stocking events and habitat enhancement projects. Lastly, social learning within the RRCC has led to collaborations among members unrelated to Robust Redhorse, indicating a transferable effect of social learning within a stakeholder group benefiting conservation efforts beyond the original focus.

STUDY LIMITATIONS & FUTURE RESEARCH DIRECTIONS

Our population dynamics models for Sicklefin Redhorse and Robust Redhorse did not include environmental variables. Including environmental factors (e.g., water temperature), which could potentially impact survival and recruitment of the population, could help shed light on how population status may change in the future either with or without management actions. Additional population characteristics that may be considered in future iterations of the models include whether individuals spawn every year or if they skip years between spawning and sex-specific survival probabilities.

Conservation solutions are seldom “win-win” situations, and trade-offs between competing objectives are usually inevitable (McShane et al. 2011a; McShane et al. 2011b). The adaptive management framework developed for Robust Redhorse did not include obviously competing objectives, and therefore potential trade-offs were not directly evaluated. Further explorations of objectives such as minimizing cost of management actions could potentially be included in future iterations of the SDM and AM framework to better help stakeholders make management decisions.

Although the Sicklefin Redhorse Conservation Committee is not currently focused on using SDM to make management decisions, the species could potentially benefit from the process. Thus far, most of the research and knowledge of Sicklefin Redhorse is focused on adults (Favrot and Kwak 2018). Much uncertainty may exist about other life stages of the species that contribute to population dynamics and persistence. Employing SDM and AM approaches could help identify and reduce such uncertainties, as well as make management and monitoring objectives more explicit.

We presented a single case study for investigating how social learning occurs in the context of imperiled species conservation. To gain better understanding of commonalities and differences among collaborative conservation partnerships such as the RRCC, future research could identify organizations similar to the RRCC across taxa and geographic range to compare and contrast cases and identify organization characteristics that promote or impede learning.

Such studies have been done in river basin planning (Mostert et al. 2007; Borowski et al. 2008). Similar studies conducted in the context of species conservation may shed light on if/how social learning differs in this context compared to other environmental issues.

The Endangered Species Act (ESA) is one of the most powerful legislations dedicated to conserving wildlife and fish species in recent history. However, the strict regulations of the ESA may come with a cost. During interviews, many RRCC members stated that the Committee is united in that none of the signatories want the Robust Redhorse to be listed for reasons related to their respective missions/bottom lines. Additionally, one member went as far as expressing concern for the continuity of the partnership if the species becomes listed, citing that the extra restrictions and paperwork that come with working with an endangered species may greatly reduce stakeholders' willingness to continue participating in the collaboration to conserve the species. Therefore, examining what ESA has accomplished since it was enacted and how it could potentially impede management/learning on the ground would be informative.

REFLECTIONS ON INTEGRATIVE RESEARCH

There has been increasing attention on integrating social and natural sciences in conducting conservation research (Moon and Blackman 2014; Bennett et al. 2017). At the higher education level, this is evidenced by establishment of interdisciplinary graduate programs such as ICON, as well as schools' (e.g., Warnell) hiring of faculty with an interdisciplinary background and track record of conducting research rooted in socio-ecological theories and frameworks, suggesting that the conservation science field today is different from what it looked like 2 decades ago. That said, I believe my dissertation would have had a different focus had I pursued a degree solely in Forest Resources as opposed to ICON. For example, without taking courses outside of my own discipline and learning about environmental governance and systems thinking, I may not have thought to explore the role of social learning in decision making and adaptive management in the context of Robust Redhorse conservation, the results from which I find very fascinating, and think are worth further exploration.

As someone with background and training primarily in natural science, my focus on conservation issues had mostly been on the wildlife or fish populations themselves instead of people prior to becoming an ICON student. My idea of conservation was one that aligned more with "fortress conservation" (Robinson 2011; Sarkar and Montoya 2011) in that biodiversity should be separated and protected from human degradation of the environment. However, that quickly changed after entering the ICON program, where I learned that the natural and social world are inextricably linked, and that the "fortress conservation" mindset has several drawbacks. For example, many national parks and reserves that preclude local communities fail to recognize that their livelihood depend on the natural resources available within the preserved natural areas (Sarkar and Montoya 2011).

Looking back, my reading response from the second week of ICON8001 revealed the status of my knowledge and comfort level with various worldviews from other disciplines at the time:

> *"If I am not doing research, I tend to be more sympathetic of the fact that one person's reality can differ greatly from another person's because of their personal experiences and the culture in which they are immersed… However, when I conduct research, I tend to think more like a realist, and it is likely because that is how I was trained; namely that there is one truth out there in nature and we do our best to describe and understand it using the scientific method and tools. Same can be said with regards to epistemology. As*

a scientist, I identify most with the objectivist epistemology, while as a human being, I identify most with the constructionist epistemology… Currently, I may not feel very comfortable collaborating with people occupying ontological and epistemological points of view different from mine, mainly because I do not yet possess the communication tools to have constructive conversations with people with very different background and training from me. However, I think it is important to gain those skills, as I think that, to solve conservation issues in today's cultural and political environment, it is beneficial for conservationists to be able to communicate with researchers and stakeholders from diverse backgrounds."

Five years later, perhaps my worldviews have not shifted very much; however, I believe my ability to communicate and collaborate with researchers with epistemological and ontological views different from mine has improved greatly. I am now equipped with a better understanding of various ways our approach to conducting research is informed by both personal worldviews and professional training, and that effective conservation requires consideration and incorporation of multiple ways of knowing from diverse resource users.

At one point in every ICON student's journey, they have likely wondered whether their research is "integrative" enough. I certainly have multiple times. However, just as Hirsch and Brosius (2013) stated that "integrative" is a "*process* of bringing separate elements together", I think learning to be an integrative thinker and researcher is also a *process* that goes beyond our PhD dissertation. It is a continuous process of learning, unlearning, and reflecting on our way of thinking and how that in turn affects how we "do science". The research I presented in this dissertation is just the first step towards my development as an integrative researcher.

STRATEGIC COMMUNICATION

Throughout my PhD studies, I sought opportunities to learn and improve upon my communication skills to translate complex research into easily understandable content for a general audience. To this end, I became an author for the Athens Science Observer, where I wrote several blog posts related to environmental and conservation topics. Specifically, one blog post I wrote aimed to communicate the issue of habitat fragmentation in rivers created by hydropower dams and how it affects migratory fish such as Robust Redhorse (Appendix C). Additionally, I sought out opportunities to highlight research conducted by other researchers at UGA by writing articles in outlets that communicate science to the public. Some of my writings were published on the website of Warnell School of Forestry and Natural Resources and Warnell's alumni magazine, *the Warnell Log*. Further, as an intern at UGA's Research Communications Office in summer of 2021, I produced several other science- and research-related articles that were published on the @UGAResearch website. Aside from science writing, I also participated in outreach activities such as STEMZone, a science outreach event showcasing various science and sustainability programs at UGA and in Athens.

Communication was also critical to the progress of my research chapters that involved working with personnel and data from outside professional management agencies. Throughout the process of developing an adaptive management framework for Robust Redhorse, I communicated frequently with RRCC members both in the format of workshops and informal email exchange outside of meetings to solicit feedback on the SDM process and PVA outputs. Prior to the facilitated workshops, I prepared materials and exercises to help elicit stakeholder input. During the workshop, I did my best to ensure that all participants had the opportunity to voice their input. Following the expert elicitation workshops, I presented the scenario forecasting model to the RRCC at annual meetings to update the Committee on the progress. Lastly, prior to collecting interview data for Chapter 4, I communicated to the interview participants the purpose of our study and how their responses regarding their experience being a member of RRCC will help us understand the role of social learning in imperiled species conservation. I also gave potential participants opportunities to ask any questions they had regarding the study prior to signing up for the study. Additionally, I prepared an executive summary of the major findings from the social learning study to be distributed to interview participants (Appendix D).

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APPENDIX A. COMPLETE MANAGEMENT OBJECTIVES TABLE WITH PERFORMANCE STATISTICS FOR EACH MANAGEMENT UNIT OF ROBUST REDHORSE POPULATIONS, INCLUDING PERFORMANCE METRICS THAT WERE NOT EVALUATED BY THE PVA IN THIS STUDY.

Means Objectives	Performance statistics	Altamaha	Broad (GA)	Savannah	Pee Dee	Evaluated by PVA
Stable or increasing population size	Average adult abundance over last 25 years of simulation	1000	300	1000	500	Yes
	% of starting adult population size at end of simulation (relative metric - +, -, or =)	increasing	stable	stable	increasing	Yes
	% of simulated populations that drop below an abundance threshold	<10%	<5%	<1%	<10%	No
	Population growth rate over simulation period (lambda)	Average lambda >1	Average lambda >1	Average lambda >1	Average lambda >1	Yes
Population persistence	Probability of persistence (calculate from PVA) over simulation period	>0.95	>0.95	>0.95	>0.95	Yes
Self-sustaining population	Average number of new adults (age 4) each year over the last 25 years of the simulation	> or = to adult mortality rate	> or = to adult mortality rate	> or = to adult mortality rate	> or = to adult mortality rate	No
	Number of years with recruitment over last generation of simulation	Not provided	Not provided	Not provided	Not provided	No

Maintain adaptive potential	Average annual number of new juveniles over the last 25 years of the simulation	< or = to population mortality rate	< or = to population mortality rate	< or = to population mortality rate	< or = to population mortality rate	No
	% of expected heterozygosity maintained over the simulation period	90%	90%	90%	90%	No
	Inbreeding coefficient over the last generation of the simulation	not to exceed ±0.10	not to exceed ±0.10	not to exceed ±0.10	not to exceed ±0.10	No
	Effective population size over the last generation of the simulation	50	50	150	100	No

APPENDIX B. SEMI-STRUCTURED INTERVIEW QUESTIONS FOR ASSESSING SOCIAL LEARNING WITHIN THE ROBUST REDHORSE CONSERVATION COMMITTEE

1. Background information
    a. Q: Can you describe your professional background and how you became involved with the Robust Redhorse Conservation Committee?
        i. Q: How long have you been/were you involved with the RRCC?
        ii. Q: What is your current role/connection with the RRCC?
    b. Questions for individuals who were part of the RRCC but are no longer involved (exclude those who are no longer involved due to retirement)
        i. What were the reasons why you left the RRCC?
2. Values and perception
    a. Overall values and perception
        i. Q: Can you describe your understanding of Robust Redhorse, the threats they face, and efforts aiding in their recovery prior to joining the RRCC? How has your understanding changed since you joined the RRCC?
        ii. Q: How has your perception of the ecosystem within Robust Redhorse's range changed as a result of collaborating with other RRCC members?
3. Knowledge and skill acquisition
    a. Q: What knowledge have you gained about Robust Redhorse and their habitat as a result of collaboration and discussion with other RRCC members?
    b. Q: What are some techniques and skills that you have learned or developed with other RRCC members specifically for helping with Robust Redhorse population monitoring and recovery?
4. Perceptions specific to the RRCC
        i. Q: What are some of the strengths/resources that RRCC has at its disposal in helping Robust Redhorse populations recover?
        ii. Q: What kind of opportunities that are currently available to the RRCC in helping Robust Redhorse populations recover?
        iii. Q: What abilities or opportunities does RRCC currently lack to help Robust Redhorse populations recover?
        iv. Q: How do you feel about the progress that has been made with Robust Redhorse conservation so far?
            1. Q: If progress is limited, what are some of the challenges (both internal and external to the RRCC) preventing the group from making sufficient progress in Robust Redhorse recovery efforts and achieving its long-term goal (recovery of RRH in its historic range)?

v. Q: Can you provide examples of success stories related to Robust Redhorse conservation/management as a result of inter-agency/sector collaboration?

vi. Q: Who are actors you think should be included but is not currently part of the RRCC and how would the Committee benefit from including those actors?

b. Perception of other members

i. How well did you understand the roles of other RRCC partners in conservation of imperiled species like Robust Redhorse when you first joined the Committee? How has that understanding changed over time?

ii. Q: What have you learned about other members' values and views regarding Robust Redhorse conservation through collaborating with them?

5. Relationships/interactions among members

a. Overall relationships/interactions

i. Q: Can you describe your professional relationship with the other members of the RRCC prior to your involvement with the group? How have those relationships changed since you joined the group?

ii. How has your own professional network changed since joining the RRCC? How has the change affected other projects in which you are involved?

iii. Q: What collaborations have you initiated with other RRCC members as a result of RRCC collaborations a result of the working relationship you established through RRCC?

iv. Q: How often do you interact with other members of the RRCC, and in what format (formal meetings, emails, etc.)?

v. Q: Under what settings do you interact with other RRCC members outside of annual meetings (e.g., professional society meetings, inter-agency meetings, etc.)?

b. Interactions/experiences during annual meetings

i. Q: How do you think the annual meetings help RRCC make progress towards its goal(s)?

ii. Q: Is the material shared at RRCC meetings presented in an easily understandable way?

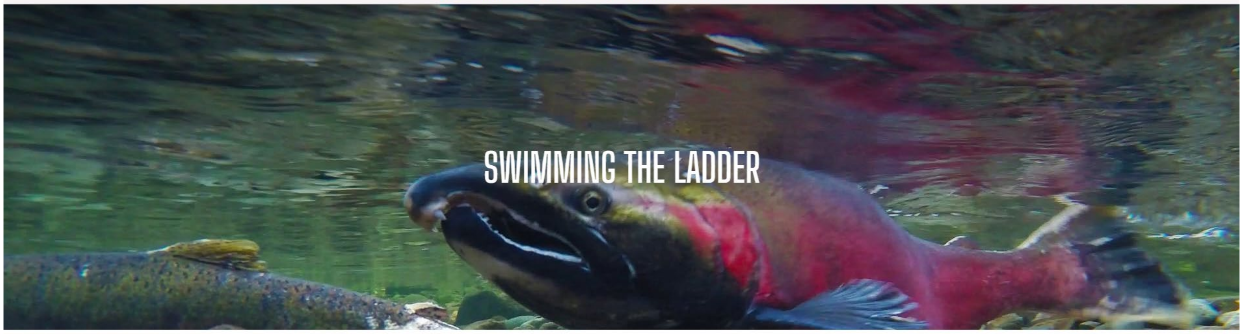
1. Q: How can communications at the meetings be improved?

iii. Q: Do you feel that the discussions regarding Robust Redhorse monitoring, research and management efforts during the annual meetings are often productive? Why or why not?

iv. Q: Do you feel that your opinions were taken seriously during the discussions at the annual meetings?

v. Q: Have you disagreed with someone regarding management approaches for Robust Redhorse recovery? If so, how were those disagreements handled during the meeting?

APPENDIX C. BLOG POST ABOUT HYDROPOWER DAMS AS FISH MIGRATION BARRIERS PUBLISHED ON ATHENS SCIENCE OBSERVER.



SWIMMING THE LADDER

October 9, 2018 7:45 am

athensscienceafe

The annual upstream migration of salmons to their spring spawning habitat is fairly well-known. However, most people may not know that this behavior is common among other fish species as well, including sturgeons, American shad, and American eels. The distance that fish travel during migration can vary widely – some fish do not need to migrate very far to reach their spawning habitats to reproduce, while salmons can travel for up to 200 miles to reach theirs. A bit too far for a booty call, if you ask me.

Coho Spawning. Image Credit: Bureau of Land Management Oregon and Washington via Flickr. Licensed under CC BY 2.0.

Unfortunately, there are currently barriers in the streams and rivers around the world that can hinder fish migration and have negative impacts on fish populations. For example, if a fish's migratory route is obstructed, they cannot reach their ideal spawning ground, and thus may forego producing offspring altogether. As a result, the number of new members being recruited into the population will decrease, and the population abundance will decline over time.

Common types of fish migration barriers include culverts, dams, and levees. There are currently more than 4,600 dams in Georgia alone, and the robust redhorse is an example of a fish species that occurs in Georgia whose migratory paths have been blocked by these dams. Adult robust redhorse prefer gravel patches that only occurs at certain spots in rivers for spawning. The dams prevent them from getting to those spawning habitats which is thought to contribute to their population decline.

Road culvert. Image Credit: kghopkin via Flickr. Licensed under CC BY-NC 2.0.

While the most straightforward way to mitigate the negative effects of migration barriers is to remove the barriers themselves, this approach is often not feasible because these structures are used by humans for many purposes. For example, hydroelectric dams are used by power companies to generate power for nearby residents. Since removing the barriers is often not an option, the next best thing is to help fish get over the barriers during migration. There are several ways to help facilitate fish migration. Amusingly, an ingenious method is the fish cannon produced by a company named Whooshh. The fish cannon helps fish get over dams by, you guessed it, launching them from a â€œcannonâ€ made up of a flexible tube over the barriers. Once the fish is inside the tube, a difference in pressure in front of and behind the fish acts as a force that pushes the fish from one end of the tube and out the other.

Shasta dam. Image Credit: Amit Patel via Flickr. Licensed under CC BY 2.0.

A more traditional and widely used method for facilitating fish movements is fish passageways, or fish ladders. There are several different designs for fish ladders, but the basic idea is that they are made up of an ascending series of small pools extending from the bottom of the dam to the top. Since the difference in height between the pools are short, fish can swim from one pool to the next fairly easily until they make it over the dam. Fish ladders can be found at certain dams in Georgia, such as the Juliette Dam made famous by the movie Fried Green Tomatoes.

One size does not fit all when it comes to fish ladder designs, however. For example, some fish ladders only work for good swimmers like the robust redhorse or salmon, but not for other fish such as American shad. A recent study showed that, less than 3% of American shad made it through all of the dams with fish ladders to their spawning habitats in three major rivers in the northeastern U.S.

Another potential downside of fish ladders is that, while they can help facilitate upstream migration, they are not as good at helping fish move downstream, which is important for fish that make roundtrip migrations and whose offspring need to migrate downstream to mature.

In the ParanÃ¡ river in Brazil, the fish passageways near dams actually act as â€œecological trapsâ€ that do more harm than good for the fish populations. In this case, when fish encountered the dams while swimming upstream, they used the ladder to get to the other side where the habitat condition was actually worse for spawning. If the ladder was not there, the fish could have stayed on the downstream side of the dam and looked for suitable habitats in the tributaries (side streams).

Fish Ladder, Nimbus Fish Hatchery. Image Credit: ray_explores via Flickr. Licensed under CC BY 2.0.

While fish ladders may not be a panacea for mitigating fish migration blockage, it is a way to help some fish migrate when barrier removal is not feasible. Additionally, some improvements have been made to make fish ladders more safe and efficient for fish passage. So, the next time you see a fish swimming upstream in a river, remember how many obstacles stand in their way to find mates, and how easy we humans have it in comparison!

APPENDIX D. EXECUTIVE SUMMARY OF STUDY ASSESSING SOCIAL LEARNING WITHIN RRCC TO BE SHARED WITH INTERVIEW PARTICIPANTS.

Study title

Identifying social learning outcomes and factors affecting learning among stakeholders in the context of Robust Redhorse conservation

Background

Natural resource managers often need to confront many challenges and uncertainties when attempting to solve complex environmental problems. Social learning, whereby a diverse stakeholder group co-produce knowledge and understanding surrounding an environmental problem through collaboration and deliberation, could potentially help increase the group's ability to adapt to unforeseen changes to the conditions under which they operate. Through collaborating and discussing the issues at hand, managers could also learn more about each other's views and potentially develop trusting relationships. As such, social learning could also lead to more stakeholder buy-in on potential solutions and management actions. While there are many studies investigating social learning in natural resource management, few examined its role in imperiled species management. The goal of our study was to develop an empirical case study of social learning in the context of Robust Redhorse conservation. Our three main research questions are:

1) Has social learning occurred as an outcome of collaboration and deliberation among stakeholders? If so, what types of learning has occurred?
2)What factors act as facilitators or barriers to the social learning process?
3)Does social learning lead to collective actions that benefit the species or the environment?

Approach

To help identify evidence of learning as well as factors that may affect learning among stakeholders of the Robust Redhorse Conservation Committee, we used two main approaches to collect data: 1) review of annual meeting summaries and 2) semi-structured interviews. When reviewing the meeting summaries, we looked for what has been learned by RRCC members through collaboration and deliberation, as well as characteristics related to how the meetings are run that could affect the deliberation process. During January – March 2022, we also conducted interviews with RRCC members with a set of predetermined questions to gain a better understanding of their experience since joining the RRCC. After interviews were transcribed using an online transcription software (otter.ai), we read through the transcripts to identify any themes emerging from the texts that could help answering our research questions.

Key findings

What has been learned

Through analyses of annual meeting reports and interview transcripts, we identified several areas where RRCC members have learned together about Robust Redhorse and the ecosystem in which the species occurs. First, annual reports showed that, through collaborative monitoring and research activities, RRCC members have gained substantial knowledge about the natural history of Robust Redhorse, such as habitat preference, spawning behavior, movement, genetics of evolutionary significant units, and more.

Some interviewees stated that they have learned more about the role of various agencies/companies in Robust Redhorse conservation. Many also said that they have learned more about other members' values and viewpoints through collaboration. Many praise the members' passion and dedication for helping the species recover, while also recognize that those values do not always translate to the mission/mandate of their employers.

Lastly, most interviewees indicated that their professional network has expanded as a result of joining the RRCC which benefit them not only with collaborations on Robust Redhorse related projects, but also other species conservation efforts as well.

What affects learning?

Diversity of stakeholders: RRCC consists of stakeholder from different sectors. The diversity can facilitate learning among members because members from different backgrounds can help contribute to framing of the problem or developing potential solutions. Additionally, there are also stakeholders who have been members since the beginning, as well as those who joined in the last 3–5. The different lengths of involvement also helps facilitate learning because older members can provide institutional knowledge and share their experience, while newer members can bring fresh perspectives or new skillsets to the table.

Frequent and sustained engagement: There are several ways that RRCC members can engage with one another. First, the annual meetings provide a space for members to provide updates on research and monitoring progress and receive feedback from other members. The annual meetings are also a good place to build new or strengthen existing relationships. Many members said that the social aspects of the annual meetings are important for not only relationship building, but also further exchange of ideas in a more relaxed setting, which many stated was lost during the virtual meetings in 2020 and 2021. Outside of annual meetings, many members also meet or communicate via email regarding specific issues related to Robust Redhorse conservation. The technical working groups also meet at least once a year outside of Committee's annual meetings to plan for monitoring and research activities. The frequent and sustained communication among members likely facilitated learning among the members.

Quality of information exchange: While most interviewees stated that the materials presented during the RRCC annual meetings are easily understandable by everyone, a few expressed that, as new members, sometimes it was difficult for them to understand certain aspects related to management, such as delineation of evolutionary significant units. Additionally, some members expressed that the presentation of material sometimes fail to connect back to overarching goals of the Committee.

Quality of discussions: RRCC members stated that they think the discussions during the annual meetings are generally productive and that they feel that their opinions are taken seriously by the group during discussion, although one respondent said having a third-party facilitator could help focus the discussions and help the group make decisions under uncertainty or differences in opinions. Third-party facilitators were present at earlier meetings of the RRCC because those meetings were more "contentious" according to older members who were present at those meetings. However, the practice of inviting facilitators to the annual meetings was discontinued. Although recent meetings are not as "contentious", it could still benefit the group to invite third-party facilitators to help guide the meetings.

Does learning lead to collective action?

Our findings suggest that social learning among RRCC members have led to several collective actions taken by the group, including implementing management actions to help achieve the Committee's long-term goal of establishing six self-sustaining populations within the species range. These actions include introduction of new populations and augmentation of existing Robust Redhorse populations, actions aimed at improving spawning habitat such as manipulating water flow in the system during spawning and rearing seasons and augmenting gravel bars to create more spawning habitat. However, the outcomes of these collective actions remain unclear. This could be due to the timeframe of population recovery taking longer because Robust Redhorse is a long-lived fish, or perhaps the initial assumptions about factoring limiting population growth and recruitment need to be revisited.

Several members indicated that they also collaborated on projects outside of the RRCC as a result of the working relationships that they developed through RRCC. An example of this would be the Candidate Conservation Agreement with Assurances developed by Georgia DNR, Georgia Power Company, and the U.S. Fish and Wildlife Service to implement conservation actions for the mussel species in Georgia.