Final Report

Project Title: Development of Restoration Criteria for Freshwater Mussel Species in Greatest Need of Conservation

Project Number: T-99-R-1

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Background and Objectives:

The objective of this project was to provide a detailed investigation into the restoration options for specific mussel species in greatest conservation need (SGCN). We first wanted to determine the dominant factors limiting distribution of particular mussel SGCN and then investigate potential restoration options. Example restoration options include in-stream habitat restoration, re-establishment of host fish, and/or mussel augmentation. While an ideal situation for re-establishment of freshwater mussels would exist in the form of natural recolonization, research indicates that this process is unlikely to occur in certain situations (e.g., critically small populations or populations separated from source mussels by impoundments) or may take many years to occur in optimal situations (e.g., natural recolonization in unimpounded waterways). This project provides an example framework to inform managers of optimal restoration options for a specific scenario.

This project was an initial step to provide guidance to state entities on the direction of restoration efforts for mussels in wadeable streams. Previous research of state wildlife grants T-53 and T-82 established the need for potential restoration action in targeted regions in Illinois. Reach-scale restoration efforts are occurring throughout Illinois to improve in-stream habitat, but augmentation of populations of SGCN may be necessary to re-establish viable communities. Investigating restoration criteria and feasibility is a necessary component to determine the future approach for conserving mussels in greatest need of conservation. This project combined previously collected data in a Bayesian Network to explore restoration options for mussel SGCN. Bayesian Networks have been used in natural resource management (Marcot et al. 2001; Andersen 2010; Kwak et al. 2011) because empirical data, professional opinion, and other parameters of interest (e.g., financial investment) can be incorporated in a relational framework to optimize an outcome. We utilized Bayesian modeling software Netica (version 5.12 or later, Norsys Systems Corporation, Vancouver, BC, Canada) because it is a user-friendly, widely-available software networking tool for relational networks.

Summary:

During this project period, INHS personnel developed models to investigate restoration options for specific SGCN mussels (outlined for each job under *Species Specific Approach*) and also considered restoration of species richness (outlined for each job under *Species Richness Approach*). We published one peer-reviewed article, submitted another publication for peer-review, presented project-specific data at conferences, completed two INHS technical reports, led a workshop focusing on Bayesian networking methods, and compiled data that can be accessed by future researchers interested in using Bayesian networking tools for natural

resource decision-decision making. We have attached previous interim reports as a guide for progress over this project's timeline (Appendices I-IV for interim reports 2016-2019; linked in pdfs; note that all references to Appendices in each interim report have been updated to match what is in this Final Report) and major accomplishments are summarized for each Job. All associated data files for model building and analysis will be provided to Illinois Department of Natural Resources staff or available via request from Principle Investigators at the Illinois Natural History Survey.

An overview of the steps followed during this project are:

Step 1. Identify Objectives (see Job 1)
Step 2. Conduct Preliminary Analyses (see Job 2)
Step 3. Determine possible management actions and assess preliminary costs (see Jobs 1-2)
Step 4. Construct model (Job 3)
Step 5. Organize and incorporate empirical data (Job 3.1)
Step 6. Collect expert opinion responses (Job 3.2)
Step 7. Compile and validate model (Job 3.3)
Step 8. Determine sensitivity (Job 4.1)
Step 9. Test specific sites (Job 3.3; Job 4.2)
Step 10. Assess feasibility, carry out management, and monitor results (Job 4.2 & new research)

Mussels collected during species richness sampling in the Salt Fork Vermilion River.

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Job 1: Determine target areas for necessary re-establishment of freshwater mussels in Illinois.

Summary: Based on previous data from state wildlife grants T-53 and T-82, we selected 2 SGCN mussel species that met the criteria as needing potential restoration and one focal region to build initial models. Once the base work was complete for these species-specific models, we took a broader approach that focused on species richness. Some restoration measures, such as reducing nutrient loads in a watershed, may have a goal of increasing richness of species rather than increasing abundance or presence of a specific species.

Staff presented the initial results of Job 1 at the Freshwater Mollusk Conservation Society International Symposium in Cleveland, Ohio (Douglass et al. 2017; Appendix V)

1.1 Review suggested actions completed in T-82 regarding mussel SGCN populations in Illinois and choose at least 2 mussel SGCN (or richness) as candidate species for potential restoration.

Species Specific Approach: (summarized in T-99-R-1-2016 interim report [Appendix I]; completed as of 1st quarter of 2016)
We selected two focal mussel species based upon data from T-82 and information from the Chicago Wilderness area on an initiative by Openlands to conserve imperiled mussel species. Ellipse (*Venustaconcha ellipsiformis*) and Spike (*Eurynia dilatata*) were selected as focal species for T-99. Ellipse is currently listed as a SGCN in Illinois and is found in small to medium sized streams with stable substrate and swift current. This species has exhibited a 28% decline from their historic distribution in Illinois and may be at risk from habitat fragmentation, habitat degradation, and low population numbers (Douglass and Stodola 2014). Ellipse was included as one of 12 Priority Species identified to receive increased conservation efforts in an initiative announced by Chicago Wilderness and Openlands via a press release (2016). Chicago Wilderness is a regional alliance of ~260 public and private entities focused on conservation of natural resources in the Chicago Wilderness region, which includes portions of 18 counties in northeast Illinois. The selection of Ellipse for T-99 provided data-driven evaluations of potential restoration actions for the Priority Species initiative.

Spike is currently listed as Endangered in Illinois (recently changed from State Threatened to Endangered in 2020). Spike occur in medium to large rivers and has exhibited a 55% decline from their historic distribution in Illinois. In many of the areas where Spike still occurs, the populations are limited to a small number of non-reproducing individuals. Spike were historically widespread and abundant throughout Illinois, but have experienced precipitous and enigmatic declines statewide over the past four decades.

Species Richness Approach: (summarized in T-99-R-1-2019 interim report [Appendix IV]; completed as of 1st quarter of 2019)
We and staff with Illinois Department of Natural Resources discussed the potential of a tool with a broader focus on mussel community richness that could be applied to other areas within the state. The Streams Campaign (Hinz et al. 2015) and the Illinois Nutrient Loss Reduction Strategy (NLRS 2019) indicated that reduction of nutrient loads in watersheds was an objective to improve water quality. We gathered data detailing locations and areas where land use practice changes have occurred. We developed a new goal to build Bayesian Belief Networks to assess the effects of nutrient reduction strategies on mussel community richness in Illinois.

1.2 For each species (or richness) identified in Job 1.1, we will select at least 1 potential region within Illinois in need of mussel restoration.

Species Specific Approach: (summarized in T-99-R-1-2016 interim report [Appendix I]; completed as of 2nd quarter of 2016)
We chose the Chicago Wilderness region as a focal area for the species-specific models. This region includes portions of 18 counties in northeast IL and encompasses portions of the Des Plaines, Fox, Kishwaukee, and Kankakee River basins. Both Ellipse and Spike persist in portions of this region and were excellent candidates to consider concurrently.

Species Richness Approach: (summarized in T-99-R-1-2019 interim report [Appendix IV]; completed as of 1st quarter of 2019)
We gathered available land use data and coordinated with USDA-NRCS for project specifics regarding Illinois' Nutrient Loss Reduction Strategy (NLRS). Through this work, we chose the Embarras and Vermillion-Wabash drainages as focal regions to consider restoration efforts for species richness, rather than a single species restoration. The Vermilion-Wabash area has undergone a significant amount of land use improvement, largely through the creation of riparian buffers and changes in tillage practices. Conversely, officials reported little change in the Embarras. For model validation purposes, the Salt Fork Vermilion River and Embarras River were chosen as representative areas for field sampling during 2019 (see Job 3.3).

Job 2: Compile component data for mussel, fish, and habitats to inform decision tool for the regions identified in Job 1.2.

Summary: We used this opportunity to complete a quantitative assessment of mussel presence based on environmental variables from the Chicago Wilderness area (Chiavacci et al. 2018;

Appendix VI), which informed the Bayesian Decision Network nodes in Job 3 for both the species specific models for Spike and Ellipse, and the species richness models (with some modifications). A snapshot of these data were presented at the Illinois American Fisheries Society and Freshwater Mollusk Conservation Society symposium in 2017 (Appendix VII).

2.1 Organize freshwater mussel data collected during T-53 and T-82 for use in a BBN.

Species Specific Approach: (summarized in T-99-R-1-2016 interim report [Appendix I]; completed as of 2nd quarter of 2016)
We obtained and organized all known records of mussel sampling locations within the Chicago Wilderness region and supplemented T-53, T-82 and INHS Mollusk Collection data with mussel data provided by the McHenry County Conservation District. We used Ellipse and Spike presence and absence from 1990–2015 at mussel sampling locations as a response variable in a logistic regression analysis designed to determine factors influencing the presence of Ellipse and Spike. Several variables were shown to be good predictors for both Ellipse and Spike presence in the Chicago Wilderness, including the number of pollution dischargers (from the National Pollutant Discharge Elimination System, NPDES, database), fish richness (in the form of either host richness [Ellipse] or total fish richness [Spike]), presence of dams, and flow variables. In our study, we found that five factors were significant for Ellipse (factor, relationship): number of upstream dams (-), number of pollutant dischargers (-), host fish richness (+), mean annual duration of extreme low flows [-], and number of sites unsuitable for aquatic life [-]. Four similar yet distinct factors were significant for Spike: distance to downstream dam [+], high flow variation [+], number of pollutant dischargers [-], and host fish richness [+]. We found that each species responded differently to each variable, which confirms the need for managers to analyze and interpret data specific to their system prior to entering a decision making framework.

Species Richness Approach: (summarized in T-99-R-1-2019 interim report [Appendix IV]; completed as of 2nd quarter of 2019)
Species richness data for the Embarras and Vermilion-Wabash were compiled from existing reports and from the INHS Mollusk Collection (INHS Collections Data 2019) for different time frames to serve as baseline richness values. Initially, we chose sites previously sampled during 1999 (20 years prior to this project) or later, and sampled at least one additional time since 1999. This was intended to assure multiple sampling events that were within relatively recent history and minimize the inclusion of sites with unknown or outdated information regarding richness. However, the number of sites meeting these criteria was low for the Vermillion-Wabash drainage, so additional sites that fell outside of this guideline were added to achieve

desired sample size. Updated richness and density estimates were collected during the 2019 field season.

2.2 Organize host fish data for selected mussel SGCN (from Job 1.1) for use in a BBN. Gather host fish distribution data for focal sites and species from IDNR biologists and INHS collection records.

Species Specific Approach: (summarized in T-99-R-1-2016 & 2018 interim report [Appendices I & III]; data gathering completed as of 2nd quarter of 2016, data preparation for models in Job 3 completed as of 3rd quarter of 2018)

Freshwater mussels require a host to metamorphose from the larval (glochidia) stage to the juvenile stage. For most species, they rely on a fish host or suite of fish hosts for this metamorphosis and host fish identification and host quality identification is a growing research field. Many mussel species have poorly understood hosts and this lack of data has implications for management. For this project, we relied on the most recent literature available for host identification, yet we recognize that these data may change as research progresses.

- Ellipse has had successful metamorphosis to the juvenile life stage on 13 host fish species from 3 families, including sculpins, darters, and brook stickleback.
- During this project's development period, Spike host transformation data was limited to only four fish species. Coincidentally, successful host trials published in 2014 identified additional hosts for Spike, and we now understand that Spike has 33 confirmed host fish species from 10 families. Spike appears to be a host generalist, with Percids and Centrarchids being some of the more consistent hosts.
- We obtained collection records for hosts from INHS and IDNR in the Chicago Wilderness region for the host fishes of Ellipse.

Host quality differs between species. To reflect this, we developed a measure of weighted host fish quality based on the relative number of juvenile mussels that transformed on various hosts from published literature. Quality weightings were species-specific (Tables 1, 2). Where multiple sources of information on host quality existed, and where weightings did not agree among sources, the lowest weighting was chosen as a conservative measure. Host fish weights were matched with mussel presence data at each site and date for use in Job 3.

Table 1. Weighted values for Ellipse fish hosts. Hosts with <2 successfully transformed juveniles in laboratory trials are weighted at 0.25, hosts with 2-10 transformed are weighted at 0.5, 11-20 are weighted at 0.75, and >20 are weighted at 1.

Common Name	Scientific Name	Mean Transformed	Weight	Reference
Mottled Sculpin	*Cottus bairdii*	32	1	Allen et al. 2007
Slimy Sculpin	*Cottus cognatus*	48	1	Allen et al. 2007
Brook Stickleback	*Culaea inconstans*	13	0.75	Allen et al. 2007
Mud Darter	*Etheostoma asprigene*	1	0.25	Allen et al. 2007
Rainbow Darter	*Etheostoma caeruleum*	1	0.25	Allen et al. 2007
Iowa Darter	*Etheostmoma exile*	5	0.5	Allen et al. 2007
Fantail Darter	*Etheostoma flabellare*	8	0.5	Allen et al. 2007
Johnny Darter	*Etheostoma nigrum*	24	1	Allen et al. 2007
Banded Darter	*Etheostoma zonale*	1	0.25	Allen et al. 2007
Logperch	*Percina caprodes*	1	0.25	Allen et al. 2007
Blackside Darter	*Percina maculata*	2	0.5	Allen et al. 2007

Table 2. Weighted values for Spike fish hosts. Hosts with 0-20 successfully transformed juveniles in laboratory trials are weighted at 0.25, hosts with 21-50 transformed are weighted at 0.5, 51-100 are weighted at 0.75, and >100 are weighted at 1.

Common Name	Scientific Name	Mean Transformed	Weight	Reference
Eastern Sand Darter	*Ammocrypta pellucida*	10	0.25	Schroeder, Ellipsaria 2014
Rock Bass	*Ampbloplites rupestris*	15	0.25	Schroeder, Ellipsaria 2014
Rock Bass	*Ampbloplites rupestris*	1	0.25	Luo 1993
American Eel	*Anguilla rostrata*	13	0.25	Schroeder, Ellipsaria 2014
Holston Sculpin	*Cottus baileyi*	164	1	Luo 1993
Banded Sculpin	*Cottus carolinae*	3	0.25	Luo 1993
Brook Stickleback	*Culaea inconstans*	39	0.5	Schroeder, Ellipsaria 2014
Northern Pike	*Esox lucius*	21	0.5	Schroeder, Ellipsaria 2014
Rainbow Darter	*Etheostoma caeruleum*	21	0.5	Schroeder, Ellipsaria 2014
Rainbow Darter	*Etheostoma caeruleum*	3	0.25	Luo 1993
Iowa Darter	*Etheostoma exile*	9	0.25	Schroeder, Ellipsaria 2014
Johnny Darter	*Etheostoma nigrum*	103	1	Schroeder, Ellipsaria 2014
Banded Darter	*Etheostoma zonale*	3	0.25	Schroeder, Ellipsaria 2014
Banded Killifish	*Fundulus diaphanus*	11	0.25	Schroeder, Ellipsaria 2014
Blackspotted Topminnow	*Fundulus olivaceus*	57	0.75	Schroeder, Ellipsaria 2014
Longnose Gar	*Lepisosteus osseus*	17	0.25	Schroeder, Ellipsaria 2014
Green Sunfish	*Lepomis cyanellus*	12	0.25	Schroeder, Ellipsaria 2014
Pumpkinseed	*Lepomis gibosus*	19	0.25	Schroeder, Ellipsaria 2014
Bluegill	*Lepomis macrochirus*	7	0.25	Schroeder, Ellipsaria 2014
Longear Sunfish	*Lepomis megalotis*	13	0.25	Schroeder, Ellipsaria 2014
Burbot	*Lota lota*	3	0.25	Schroeder, Ellipsaria 2014
Smallmouth Bass	*Micropterus dolomieu*	39	0.5	Schroeder, Ellipsaria 2014
Largemouth Bass	*Micropterus salmoides*	148	1	Schroeder, Ellipsaria 2014
Golden Shiner	*Notemigonus crysoleucas*	1	0.25	Schroeder, Ellipsaria 2014
Yellow Perch	*Perca flavescens*	59	0.75	Schroeder, Ellipsaria 2014
Logperch	*Percina caprodes*	63	0.75	Schroeder, Ellipsaria 2014
Gilt Darter	*Percina evides*	7	0.25	Schroeder, Ellipsaria 2014
Blackside Darter	*Percina maculata*	21	0.5	Schroeder, Ellipsaria 2014
Slenderhead Darter	*Percina phoxocephala*	5	0.25	Schroeder, Ellipsaria 2014
River Darter	*Percina shumardi*	2	0.25	Schroeder, Ellipsaria 2014
Black Crappie	*Pomoxis nigromaculatus*	51	0.75	Schroeder, Ellipsaria 2014
Longnose Dace	*Rhinichthyes cataractae*	3	0.25	Schroeder, Ellipsaria 2014
Sauger	*Sander canadensis*	72	0.75	Schroeder, Ellipsaria 2014
Walleye	*Sander vitreus*	296	1	Schroeder, Ellipsaria 2014

Species Richness Approach: (summarized in T-99-R-1-2019-Q4; completed as of 4th quarter of 2019)

Mussels rely on host fish to disperse their offspring to a wider extent than would otherwise be possible, as mussels themselves are not especially mobile (Vaughn & Taylor 2000). Thus, areas with greater fish richness should generally enable greater mussel species richness as well (Schwalb et al. 2013). However, both mussel and fish richness are influenced by environmental factors such as flow, stream order, stream modification via dams and/or channelization, and food availability. This complexity of relationships is reflected in the structure of the model.

Fish richness data from the target watersheds between 1999-2019 were obtained from IDNR and compiled into model data files (see Appendix VIII).

2.3 Organize habitat associations for mussel SGCN and host fish for selected SGCN from Jobs 1.1 and 1.2 for use in a BBN.

Species Specific Approach: (summarized in T-99-R-1-2016 interim report [Appendix I]; completed as of 1st quarter of 2016)
We identified the habitat associations for Ellipse and Spike, as well as the 13 identified hosts for Ellipse and the 33 identified hosts for the Spike. These habitat associations were used to inform the metrics included in the logistic regression models (Chiavacci et al. 2018; Appendix VI).

Species Richness Approach: (summarized in T-99-R-1-2020-Q1; completed as of 1st quarter of 2020)
New habitat associations were assessed for richness models for the Embarras and Vermilion-Wabash drainages. Substrate stability was included as an indicator of physical habitat. Additionally, water quality was quantified in terms of annual number of drought days, probability of ten-year flood occurrence, percent surrounding agricultural land cover, and nitrogen and phosphorus inputs.

2.4 Gather physical in-stream parameter data for the regions identified in Job 1.2., using a combination of Qualitative Habitat Evaluation Index (QHEI; Rankin 1989), Stream Habitat Assessment Protocol (SHAP; Illinois EPA 1994), and/or the multimetric habitat index for wadeable streams in Illinois (Sass et al. 2010).

Species Specific Models: (summarized in T-99-R-1-2017 & 2018 interim report [Appendices II & III] completed as of 3rd quarter of 2018)
We examined watershed-level impacts on Ellipse and Spike presence using a mixed linear model to attempt to elucidate a broader pattern that explains Ellipse presence/absence in the Chicago Wilderness region. After researching current literature, we determined that watershed level impacts often overshadow small scale disturbances, since impacts from habitat features at larger scales tend to constrain those at smaller scales. Additionally, after the completion of the analysis on watershed level impacts, we collected site-level habitat data on both physical

habitats as well as site-specific mussel densities at sites throughout the Chicago Wilderness Area. Quadrat-specific substrate data were added for sites surveyed based on a modified Wentworth scale (percentage composition was quantified for each habitat type: clay, silt, sand, gravel, cobble, boulder, and bedrock). These data were analyzed and components of the quadrat specific habitat data were included in a peer-reviewed manuscript submission (in revision as of end of this contract in 2020). A sub-analysis of these data and the impact on growth of freshwater mussels was also prepared and presented at the Illinois American Fisheries Society and Freshwater Mollusk Conservation Society meetings in 2020 (Appendix IX).

Species Richness Approach: (summarized in T-99-R-1-2020-Q1; completed as of 1st quarter of 2020)
Additional in stream habitat information was added for all sites surveyed during the 2019 field season. Substrate measurements were not available for most sites and years included in the current model iteration. Substrate stability is a largely unquantified measure of mussel community success, although it is often cited as important. Thus, we used a uniform distribution to highlight that it should be at least considered, but it is not appropriate to determine whether or not a site has suitable substrate without conducting further site-specific research to determine any existing relationships.

Job 3: Develop a Bayesian Belief Network decision tool to provide region-specific information regarding restoration options.

Summary: The narrative for Job 3 was revised during the project revision that was approved in 2019. The primary updates included an addition of more descriptive sub-headings for Jobs 3.1, 3.2 and 3.3. For this Job, we created several Bayesian Networks to investigate relationships and decisions surrounding reintroduction of certain species (for the Ellipse and Spike models) as well as a network to investigate how species richness is impacted under different watershed scenarios.

For the Species Specific models, a series of models were created by a focus group of aquatic ecologists and were modified and adapted after several meeting sessions (a detailed summary is found in Andree et al. 2019; http://hdl.handle.net/2142/106002). These materials were presented at several professional meetings in 2018 and 2019, including Illinois American Fisheries Society, the Society for Freshwater Science meeting in Salt Lake City in 2019, and the Freshwater Mollusk Conservation Society symposium in 2019 (Appendix X & XI).

We also held a workshop in December 2019 which described Bayesian methodology and gave a hands-on walkthrough of Netica tools and usage (Appendix XII). The 6-hour workshop had 16 attendees from within the Illinois Natural History Survey, University of Illinois, Illinois Department of Natural Resources, and one attendee from Purdue University.

3.1 Create network to optimize decision-making and determine data needs for each node.

Species Specific Approach: (summarized in T-99-R-1-2018 interim report [Appendix III]; completed as of 1st quarter of 2018)

The Bayesian Decision Network (BDN) approach (Figures 1 & 2) was used to investigate restoration options of translocation of adult mussels, introduction of juvenile mussels, release of inoculated host fishes, or taking no action (e.g., relying on natural recolonization). Ellipse and Spike models using 54 combinations of stream subset (target, non-target, all streams), expert opinion statistic (median, maximum, all), and data source (long term presence, 2018 presence, 2018 abundance) were created, with examples below:

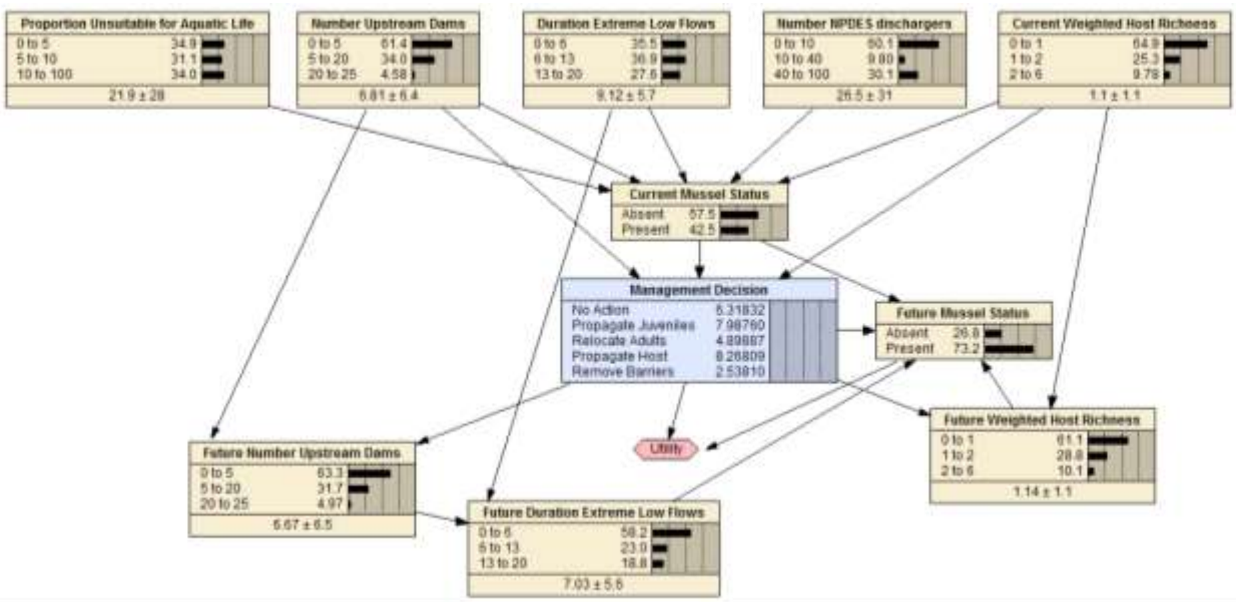

Figure 1: An example BDN for Ellipse presence. Nodes populated using existing data include Proportion Unsuitable for Aquatic Life, Number Upstream Dams, Duration Extreme Low Flows, Number NPDES Dischargers, Current Weighted Host Richness, Future Number Upstream Dams, Future Weighted Host Richness, and Current Mussel Status. Nodes populated using expert opinion and literature include Management Decision, Future Mussel Status, Cost, Utility, Future Weighted Host Richness, and Future Duration Extreme Low Flows.

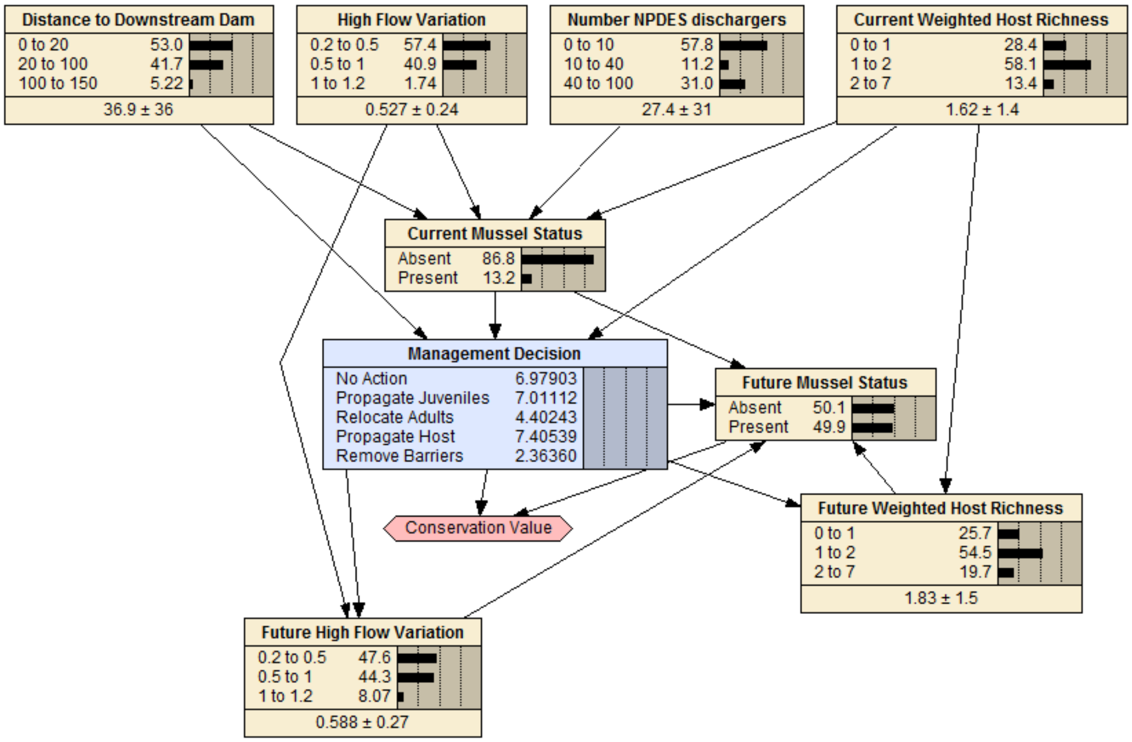

Figure 2: An example BDN for Spike presence. Nodes populated using existing data include Distance to Downstream Dam, High Flow Variation, Number NPDES Dischargers, Current Weighted Host Richness, Current Mussel Status, and Future Weighted Host Richness. Nodes populated by expert opinion include Conservation Value (Utility), Future High Flow Variation, and Future Mussel Status.

Species Richness Approach: (summarized in T-99-R-1-2019-Q4 report; completed as of 1st quarter of 2020)
A preliminary conceptual Bayesian Belief Network (Figure 3; Appendix VIII) for species richness in the Nutrient Loss Reduction target watersheds was constructed to demonstrate primary factors and their relationship to species richness based on current available literature and professional opinion. An example of one iteration of this model is below:

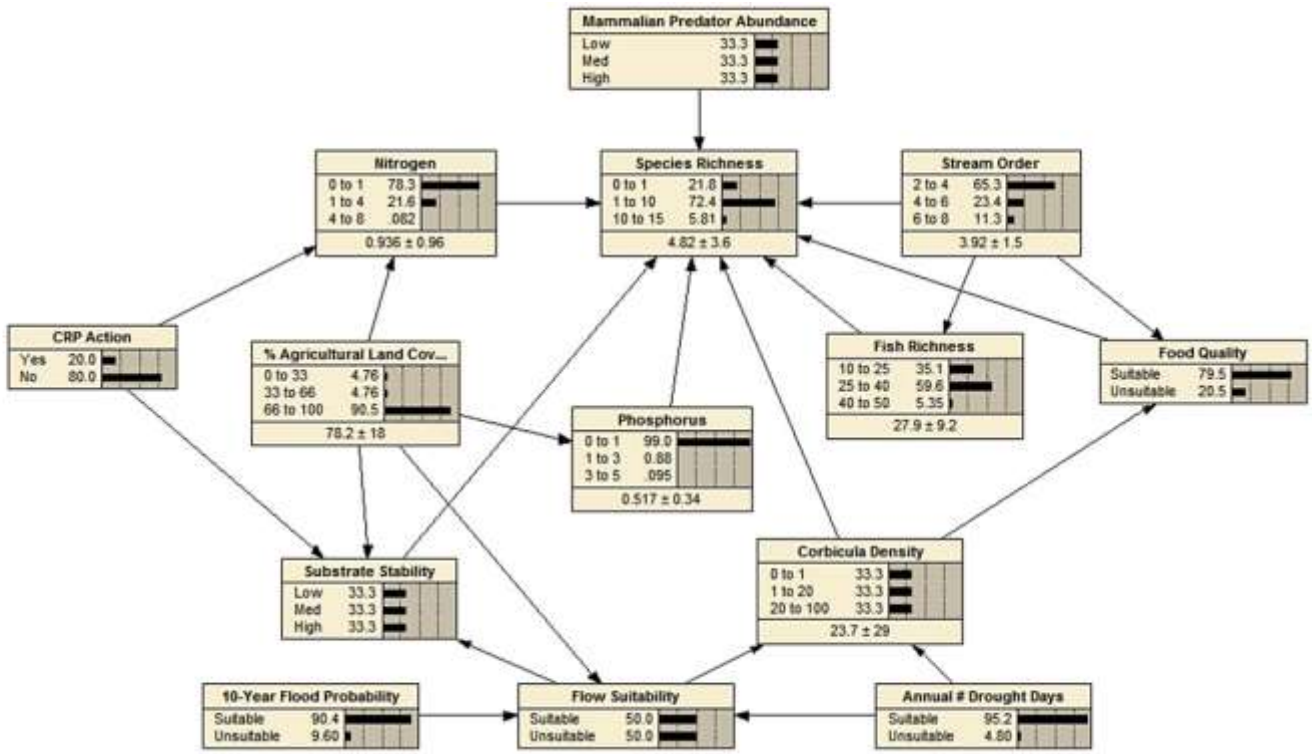

Figure 3. Structure of Bayesian belief network modeling mussel species richness for the Vermilion-Wabash and Embarras River drainages. Headings indicate factor descriptions, black bars are probabilities that each factor will be in any of its possible states or ranges of values (out of 100%). Arrows indicate relationships between factors.

The significance and background information for each node are available for future research for managers or mussel professionals.

3.2 Input empirical data and gather expert opinion for nodes that lack empirical data.

Species Specific Approach: (summarized in T-99-R-1-2018 & 2019 interim reports [Appendices III & IV]; completed as of 1st quarter of 2020)
We used empirical data to populate six nodes in Ellipse models, and five nodes in Spike models (Andree et al. 2019). Because data were pooled from multiple sources and included missing observations in some cases, we used the EM algorithm to learn from cases when populating these nodes, then compared learned probabilities to observed data distributions to assess similarity. Learned probabilities were similar to observed probabilities for all nodes, thus learning was considered successful.

In some cases, empirical data were lacking and we used expert opinion for cases where relationships are known to exist. Expert opinion was used to inform two nodes in each model: "Conservation Value" (the utility node) and "Future Mussel Status" (the parameter of interest). This was accomplished by distribution of surveys to experts, including malacologists, ecological researchers, hatchery supervisors, and agency biologists. All participants were experts in aquatic ecology and/or mussel taxonomy, ranging from 7-35 years of experience in these areas. A total of 16 experts were invited to participate, with 13 ultimately returning surveys during the allotted nine month period. Surveys were table-based and asked participants to enter their best approximation of the likelihood of an event occurring (e.g., mussel presence at a given site), given some number of other conditions (e.g., number of upstream dams, host fish richness, management action). Responses were then summarized by median, minimum, and maximum and used to populate Conditional Probability Tables (see Figure 4 for example) of model iterations corresponding to each combination of expert opinion, data set, and stream subset tested.

Current Mussel Status	Management Decision	Host Richness	Number upstream dams	Future Mussel Status	
				Present	Absent
Absent	Release Juvenile Mussels	Low	Low		
			Medium		
			High		
		Medium	Low		
			Medium		
			High		
		High	Low		
			Medium		
			High		
	Release Adult Mussels	Low	Low		
			Medium		
			High		
		Medium	Low		
			Medium		
			High		
		High	Low		
			Medium		
			High		
	Release Host Fish	Low	Low		
			Medium		
			High		
		Medium	Low		
			Medium		
			High		
		High	Low		
			Medium		
			High		
	Remove Barriers	Low	Low		
			Medium		
			High		
		Medium	Low		
			Medium		
			High		
		High	Low		
			Medium		
			High		

Figure 4. Example of expert elicitation table-based survey used for future mussel status node in Ellipse presence models. Experts were not asked to provide estimates for parts of the table where mussels were already present, as it was assumed that if mussels currently persist at a site, they will continue to do so under current conditions or with management action.

Species Richness Approach: (summarized in T-99-R-1-2019 interim report [Appendix IV]; completed as of 1st quarter of 2020)
Available long term data were added to the richness model, and literature estimates or nodes where empirical data are lacking are were included. Field data from 2019 (see Job 3.3) were added for model validation purposes.

3.3 Gather field data specific to each region and species (as selected in Job 1) as needed to provide statistical estimates of current conditions.

Species Specific Approach: (summarized in T-99-R-1-2018 & 2019 interim reports [Appendices III & IV; completed as of 4th quarter 2018)
Much of the background data were readily available from previous efforts to update prior probabilities, however validating the models and understanding precision of estimates required additional field sampling (see detailed methods in presentation in Appendix XIII). We included long-term and 2018 data from seven streams and rivers. These included our target rivers, the South Branch Kishwaukee and West Branch DuPage, and five non-target rivers that were also within the Chicago Wilderness Area and contained varying levels of target mussel species (Figure 5 and Tables 3, 4). Non-target streams were the Mazon River, Kilbuck Creek, Beaver Creek, Poplar Creek, and Ferson Creek. Estimates of abundance from long term data were used to determine which streams would be chosen to represent low (absent), moderate, and high densities of each species. These estimates were confirmed in most cases during the 2018 field season, although Ellipse densities were higher at some sites than anticipated. Models including data from target rivers only, non-target rivers only, and both target and non-target rivers were compared.

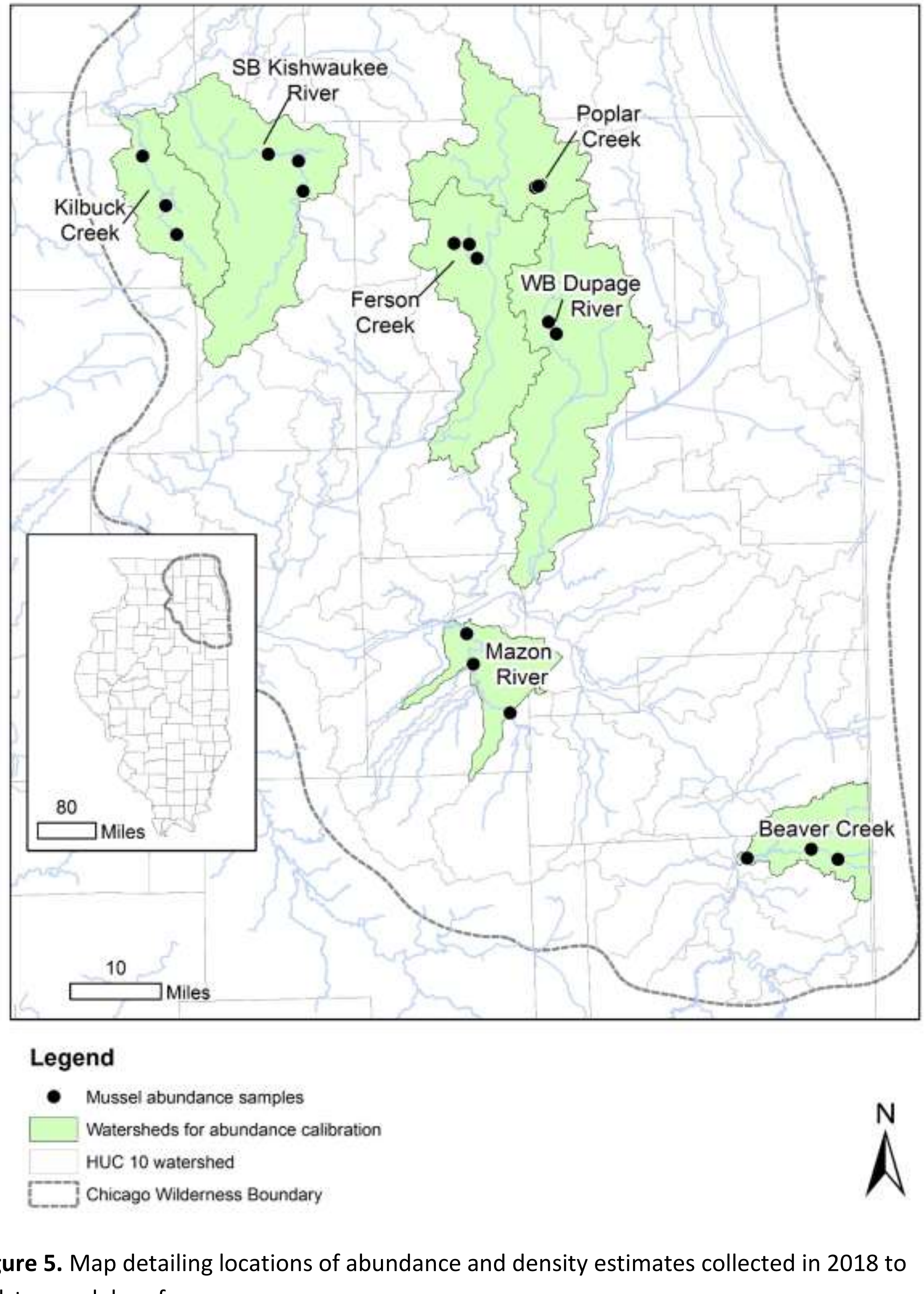

Figure 5. Map detailing locations of abundance and density estimates collected in 2018 to bolster model performance.

Table 3. Mussel abundance sampling locations and expected abundance levels (based on a priori data) for sites sampled in 2018.

Stream	Ellipse Expected Abundance	Spike Expected Abundance	Coordinates
Beaver Creek	Absent	High	40.96537, -87.59913
Beaver Creek	Absent	High	40.98205, -87.65487
Beaver Creek	Absent	High	40.9699, -87.7901
Ferson Creek	Low	Low	41.95727, -88.38954
Ferson Creek	Low	Low	41.93338, -88.34109
Ferson Creek	Low	Low	41.9556, -88.3574
Kilbuck Creek	Moderate	Moderate	42.10092, -89.05350
Kilbuck Creek	Moderate	Moderate	42.02198, -89.00423
Kilbuck Creek	Moderate	Moderate	41.975790, -88.981290
South Branch Kishwaukee River	Absent	Absent	42.043462, -88.710684
South Branch Kishwaukee River	Absent	Absent	42.10307, -88.78461
South Branch Kishwaukee River	Absent	Absent	42.09143, -88.72035
Mazon River	Absent	Absent	41.33486, -88.37375
Mazon River	Absent	Absent	41.20793, -88.28408
Mazon River	Absent	Absent	41.2862, -88.3603
Poplar Creek	High	Absent	42.04849, -88.20319
Poplar Creek	High	Absent	42.04486, -88.21442
Poplar Creek	High	Absent	42.046883, -88.207747
West Branch DuPage River	Absent	Absent	41.8298, -88.1904
West Branch DuPage River	Absent	Absent	41.8111, -88.1745

Table 4. Expected and measured density levels for sites sampled in 2018.

	Expected Density (#/m^2)		Max Observed Density (#/m^2)	
Stream	Ellipse	Spike	Ellipse	Spike
South Branch Kishwaukee River	Absent	Absent	0	0
West Branch DuPage River	Absent	Absent	0	0
Mazon River	Absent	Absent	0	0
Poplar Creek	High	Low	3.5	0
Beaver Creek	Low	High	0	3.47
Kilbuck Creek	Moderate	Moderate	6.9	0.8
Ferson Creek	Low	Low	8	0.53

Species Richness Approach: (summarized in T-99-R-1-2019-interim [Appendix IV] and Q4 reports; completed as of 1st quarter of 2020)
Much of the background data for species richness were available from previous sampling, similar to the species-specific model dataset. We created the Bayesian Belief Network to investigate how future changes to nutrient loads impact species richness, so we wanted to ensure we had relevant, present-day richness data to improve model accuracy. We ultimately sampled 9 sites each on the Salt Fork Vermilion and Embarras Rivers, and quantified mussel richness at each site (Table 5).

To make our sampling more replicable in the case of future data collection to be used in mussel richness models, we used a modified species accumulation curve approach, as detailed in a draft sampling protocol by Illinois Department of Natural Resources (IDNR 2017). A reach of ~75m was specified at the beginning of each sampling event, and this area was then sampled haphazardly for no fewer than 2 person-hours. In the event that no mussels were found within two person-hours, sampling was discontinued. Otherwise, sampling continued until 2 person-hours passed without the collection of any new mussel species (Figure 6).

Table 5. List of sites sampled during the 2nd and 3rd quarters of 2019, with observed mussel richness per site.

	Site	Common Location	Coordinates	Richness
Salt Fork Vermilion River	SF1	1.5 mi SSW St. Joseph, Co. rd. 1500N bridge	40.09174, -88.0508	0
	SF2	3 mi NNE Sidney, Co. Rd 2125E bridge	40.0702, -88.062	0
	SF3	1.5 mi N Homer, Rt. 49	40.05564, -87.95856	11
	SF6	3 mi NE Homer, above bridge	40.07365, -87.91582	9
	SF7	3.5 mi S Fithian, Co. Rd. 300E bridge	40.0652, -87.8796	8
	SF8	2 mi S Muncie	40.08891, -87.84239	9
	SF9	2.5 mi SE Muncie, mouth of Stony Creek	40.0942, -87.8164	0
	SF11	2.5 mi N Catlin, confluence with Middle Fork	40.10374, -87.71812	11
	SF12	4 mi N Fairmount, 850 East Rd. bridge	40.081007, -87.781425	0
Embarras River	E2	1.4 mi SW Camargo	39.79156, -88.1861	11
	E3	2 mi S Camargo	39.76745, -88.17615	12
	E7	3.5 mi SSE Rardin, Airtight bridge	39.55502, -88.08946	12
	E8	2 mi SE Charleston, Rt. 130 & Bypass Rd. bridges	39.4571, -88.147	7
	E9	1 mi SW Lake Charleston	39.44614, -88.15604	11
	E10	9 mi S Charleston, Ryan Bridge	39.344, -88.1706	3
	E12	Greenup, Rt. 121, boat ramp	39.2508, -88.1734	8
	E13	3 mi W Rose Hill	39.10792, -88.20951	0
	E15	1050 N bridge	39.325137, -88.146981	6

Species accumulation curves describing this pattern at all sites sampled are included in Figure below.

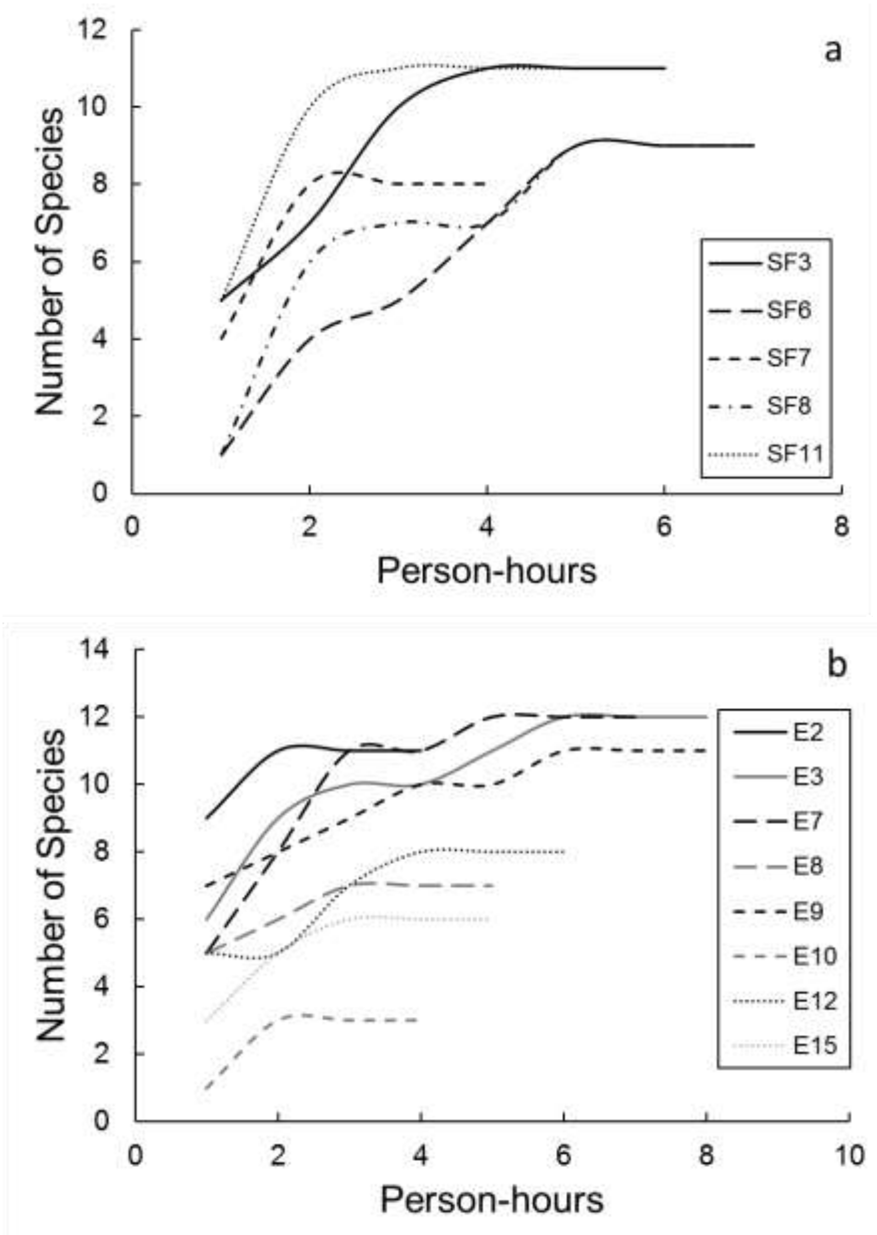

Figure 6. Species accumulation curves comparing person-hours of sampling to cumulative species richness for all site where mussel were collected on the Salt Fork Vermilion (a) and Embarras (b) rivers during 2019.

Job 4: Ground-truth BBN results for feasibility.

Summary: Two technical reports were completed that detailed the findings for original Ellipse and Spike target watersheds (Andree et al. 2020 [http://hdl.handle.net/2142/108373]). For the variables included in the richness model, a brief description of their relationship to mussel community richness and a description of how each node was populated were included in a summary report (Andree et al. 2019).

4.1 Examine output for each chosen restoration option for sensitivity (to input) and feasibility.

Species Specific Approach: (summarized in T-99-R-1-2019 interim report [Appendix IV]; completed as of 1st quarter of 2020)
Sensitivity analyses offer a means of comparing the relative importance of each factor included in a model to determining the outcome of that model. They can also be used as a way of comparing relative performance of different model versions, and thus the influence various datasets have on model outcome. We completed a sensitivity analysis for each iteration of the species specific models.

Following completion of the sensitivity analysis and all other prior jobs, the Bayesian Decision Network was used to choose an optimal decision for a specific site of interest. For managers to use this for their own purposes, the most recent available data should be used to select the appropriate current state of each node in the model for which information exists. This acts as the observation that informs the prior probabilities already added to the model, and the decision node adjusts its expected values accordingly. An example and summary of decisions for this particular application are in the figure and table below (Table 6; Figure 7):

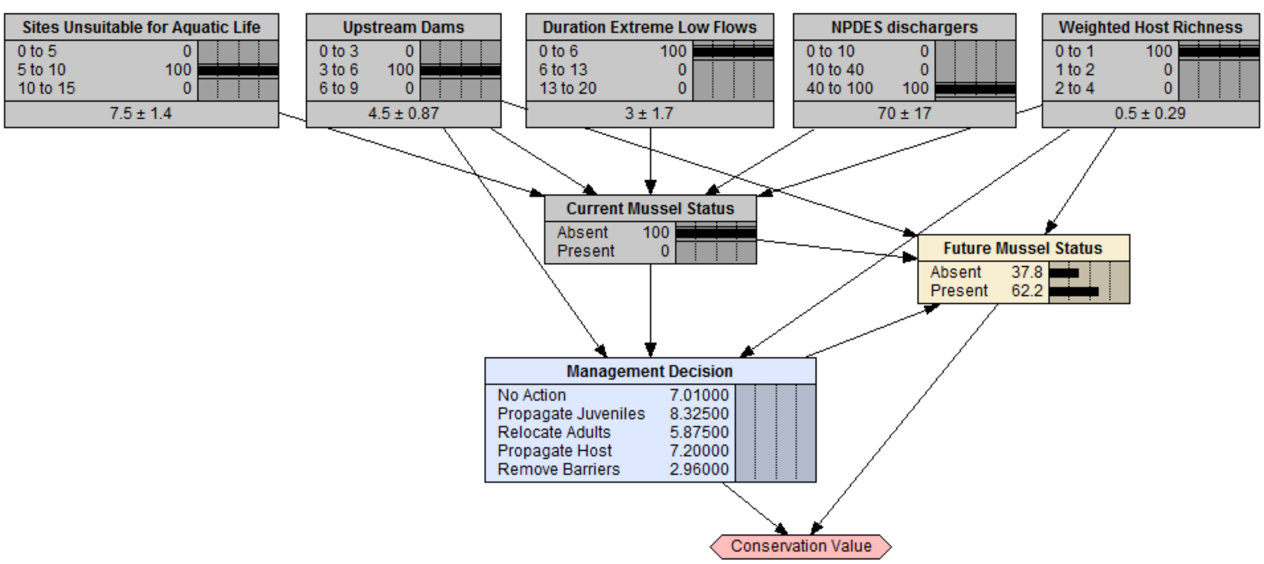

Figure 7. Example of BDN with site-specific values selected. This model included long-term presence data, median expert opinion values, and all streams data. The site specified is a portion of the West Branch DuPage River located in Warrenville, IL; a site of previous mussel restoration for juvenile *Lampsilis* spp.

Table 6. Ellipse and Spike optimal decision outcomes for two potential reintroduction sites: for the West Branch DuPage River, in Warrenville, IL, and for the South Branch Kishwaukee River, near Kingston, IL. For simplicity and because no differences in decision were observed between long-term and 2018 presence datasets, only 2018 presence and density are shown here.

Dataset	River	Species	Decision
Presence	WB DuPage	Ellipse	Release juveniles
Presence	WB DuPage	Spike	No Action
Presence	SB Kishwaukee	Ellipse	No Action
Presence	SB Kishwaukee	Spike	No Action
Density	WB DuPage	Ellipse	Release juveniles
Density	WB DuPage	Spike	No Action
Density	SB Kishwaukee	Ellipse	Release juveniles
Density	SB Kishwaukee	Spike	No Action

Species Richness Approach: (updated and completed as of 1st quarter of 2020)

Sensitivity analyses were conducted for all nodes in the richness model (Appendix VIII) for which the technique was appropriate. Criteria to be eligible for sensitivity analysis were 1) nodes must have some parent nodes and 2) nodes must have been populated by either empirical data or literature values (no nodes with uniform distribution were analyzed).

4.2 Prepare report with formal recommendation for at least 2 species for chosen species/region combinations.

Species Specific Approach: (summarized in T-99-R-1-2019 interim [Appendix IV] and Q4 reports; completed as of 1st quarter of 2020)
Two technical reports detailing findings for original Ellipse and Spike target watersheds were completed, and an example of the recommendations are seen in the table and figure in Job 4.1.

These reports were intended to provide a summary for lay persons of findings and recommendations resulting from modeling efforts completed during this project.

Species Richness Approach:
The richness models were not built as a decision network, thus there are no formal recommendations per se. However, the intent of the richness models were to serve as a starting point for managers to use in the event that a decision is made regarding nutrient loads in a watershed (Appendix VIII).

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Appendix VI: Chiavacci, S.J., A.P. Stodola, and S.A. Douglass. 2018. Natural and anthropogenic factors predict the presence of two freshwater mussels (Bivalvia: Unionidae) in Illinois, USA. Freshwater Science 37:870-884.
Appendix VII: Freshwater Mollusk Conservation Society presentation in Cleveland, Ohio - Stodola, A., S. Chiavacci, K. Stodola, and J. Tiemann. 2017. To go with the flow? How stream discharge influences freshwater mussel survival and persistence.
Appendix VIII: Mussel Community Richness Bayesian Belief Network: node data summaries
Appendix IX: Freshwater Mollusk Conservation Society poster in San Antonio, Texas - Andree, S., S. Douglass, and A. Stodola. 2020. Shell shape and body mass of two freshwater mussels differ by age and location.
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Appendix XIII: Andree, S, A. Stodola, and S. Douglass. 2018. Quantitative sampling of freshwater mussels in wadeable streams.

For all items in the Appendix, double click image to access pdf on University of Illinois Box.

Appendix I: T-99-R-1interim report 2016.

Interim Report

Project Title: Development of Restoration Criteria for Freshwater Mussel Species in Greatest Need of Conservation

Project Number: T-99-R-1

Contractor information:

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Reporting Period: 1 October 2015—30 September 2016

Project Report Due Date: 31 October 2016

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Appendix II: T-99-R-1 interim report 2017.

Interim Report

Project Title: Development of Restoration Criteria for Freshwater Mussel Species in Greatest Need of Conservation

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Appendix III: T-99-R-1 interim report 2018.

Interim Report

Project Title: Development of Restoration Criteria for Freshwater Mussel Species in Greatest Need of Conservation

Project Number: T-99-R-1

Contractor information:

University of Illinois at Urbana/Champaign
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Project Report Due Date: 1 December 2018

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Appendix IV: T-99-R-1 interim report 2019.

Interim Report

Project Title: Development of Restoration Criteria for Freshwater Mussel Species in Greatest Need of Conservation

Project Number: T-99-R-1

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Project Report Due Date: 29 December 2019

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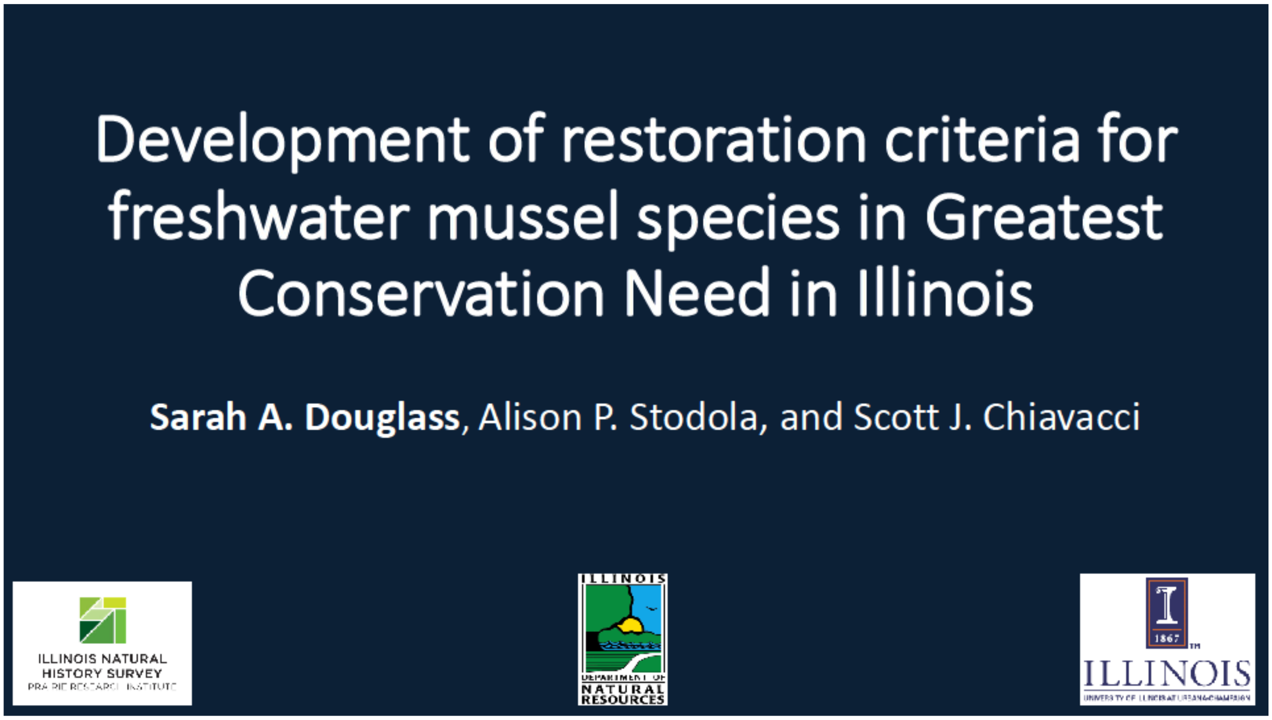

Appendix VI: Chiavacci, S.J., A.P. Stodola, and S.A. Douglass. 2018. Natural and anthropogenic factors predict the presence of two freshwater mussels (Bivalvia: Unionidae) in Illinois, USA. Freshwater Science 37:870-884.

Natural and anthropogenic factors predict the presence of two freshwater mussels (Bivalvia: Unionidae) in Illinois, USA

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Abstract: Over half of the 80 freshwater mussel species that historically occupied Illinois are now extinct, extirpated, endangered, or threatened. Two species of conservation concern that warrant further investigation are Ellipse (*Venustaconcha ellipsiformis*) and Spike (*Eurynia dilatata*). Ellipse have experienced a 30% range contraction in Illinois and are a focal species for a regional conservation initiative in the state. Spike have experienced a range contraction of 55% in Illinois, despite remaining relatively common in bordering states. Several stressors have been proposed as causes of declines in both species, such as habitat fragmentation, hydrologic alteration, pollutants, and availability of fish hosts to aid mussel dispersal. Ultimately, developing effective conservation and management actions for these species requires identifying the environmental conditions that most strongly influence their persistence. Our objective was to identify the habitat features and environmental conditions that best explain patterns in Ellipse and Spike presence in northeastern Illinois. We found that number of pollution dischargers in a watershed was a strong predictor of presence in both species. However, host fish richness, total number of upstream dams, and duration of extreme low flows were also strong predictors of Ellipse presence, whereas distance to the nearest mainstem downstream dam and variation in the number of high flow pulses predicted Spike presence. Our analysis also revealed that different mussel species may respond to the same stressors in an opposite manner, suggesting that conservation actions should either be devised on a species-specific basis or balance the needs of multiple species simultaneously. The specific predictors of mussel distribution we found represent a starting point for developing restoration strategies for these species in northeastern Illinois.

Key words: freshwater mussels, dams, pollution, streams, Unionidae, urban, water quality

Freshwater mussels are important indicators of river and lake health because they play a major role in maintaining water quality (Van Hassel and Farris 2007, Lopes-Lima et al. 2014). Freshwater mussels are also among the most imperiled organisms on Earth (Lydeard et al. 2004). North America is home to the world's richest diversity of mussels (Haag 2012), but populations of many species have declined dramatically (Ricciardi and Rasmussen 1999, Strayer et al. 2004). These declines have resulted in many mussel species being listed as endangered, threatened, or in need of conservation (Williams et al. 1993). Current means for reversing these declines remain logistically infeasible or economically impractical, even as interest in identifying the factors negatively affecting mussels increases. Thus, to mitigate these declines, we must enact appropriate and effective management actions by first identifying the factors linked to the presence of mussel species of conservation concern.

Understanding freshwater mussel declines and identifying effective restoration approaches is complicated by the multitude of pressures on mussels (reviewed in Downing et al. 2010). For example, mussels can be harmed by contaminants (Augspurger et al. 2003, Keller et al. 2007), sedimentation (Brim Box and Mossa 1999, Gascho Landis and Stoeckel 2016), changes in water temperature (Golladay et al. 2004, Spooner and Vaughn 2008), alteration of flow regimes (Layzer et al. 1993, Vaughn and Taylor 1999), invasive species (Sousa et al. 2014), over harvesting (Haag 2012), and climate change (Santos et al. 2015). Additionally, most mussels rely on a fish or amphibian host for metamorphosis and to facilitate dispersal, so factors that negatively

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Freshwater Science. 2018. 37(4):870–884. © 2018 by The Society for Freshwater Science.

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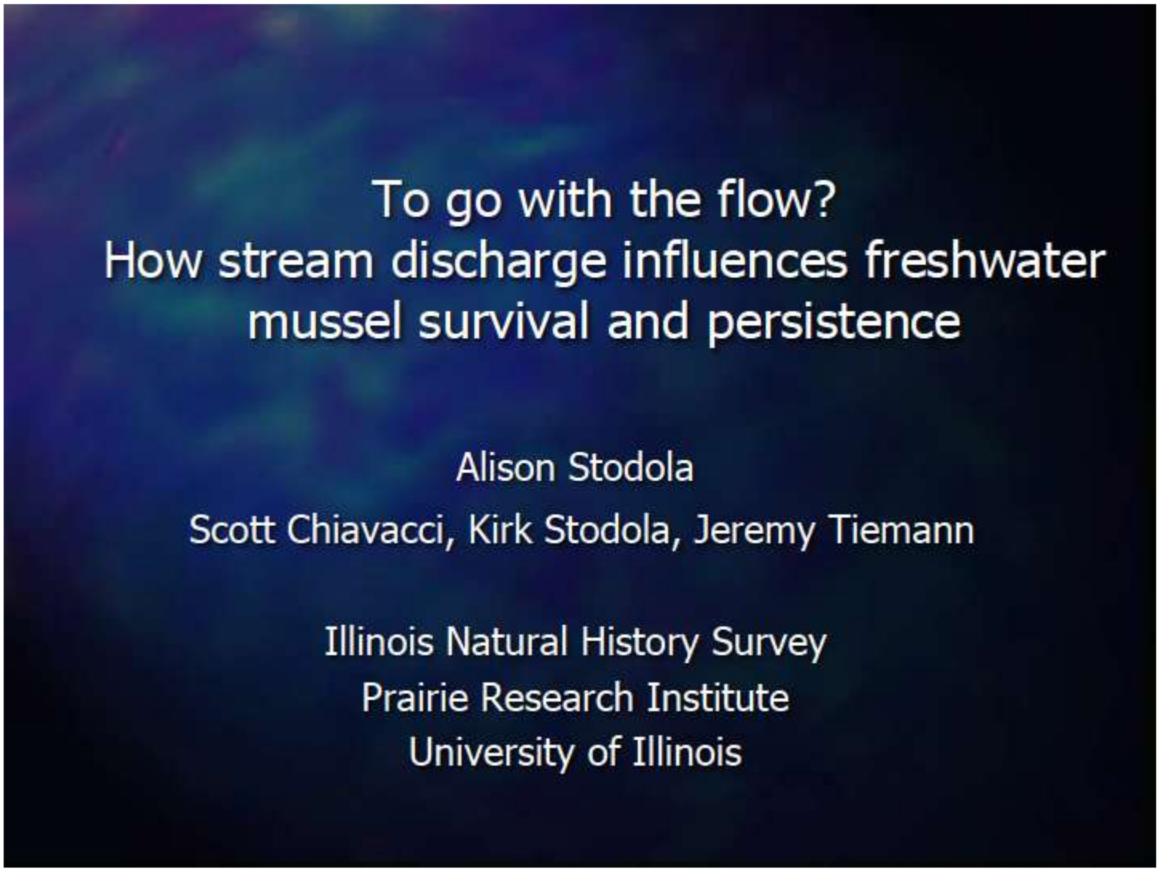


Appendix VIII: Mussel Community Richness Bayesian Belief Network: node data summaries.

Mussel Community Richness Bayesian Belief Network: node data summaries

Sara R. Andree, Sarah A. Douglass, Alison P. Stodola

2020

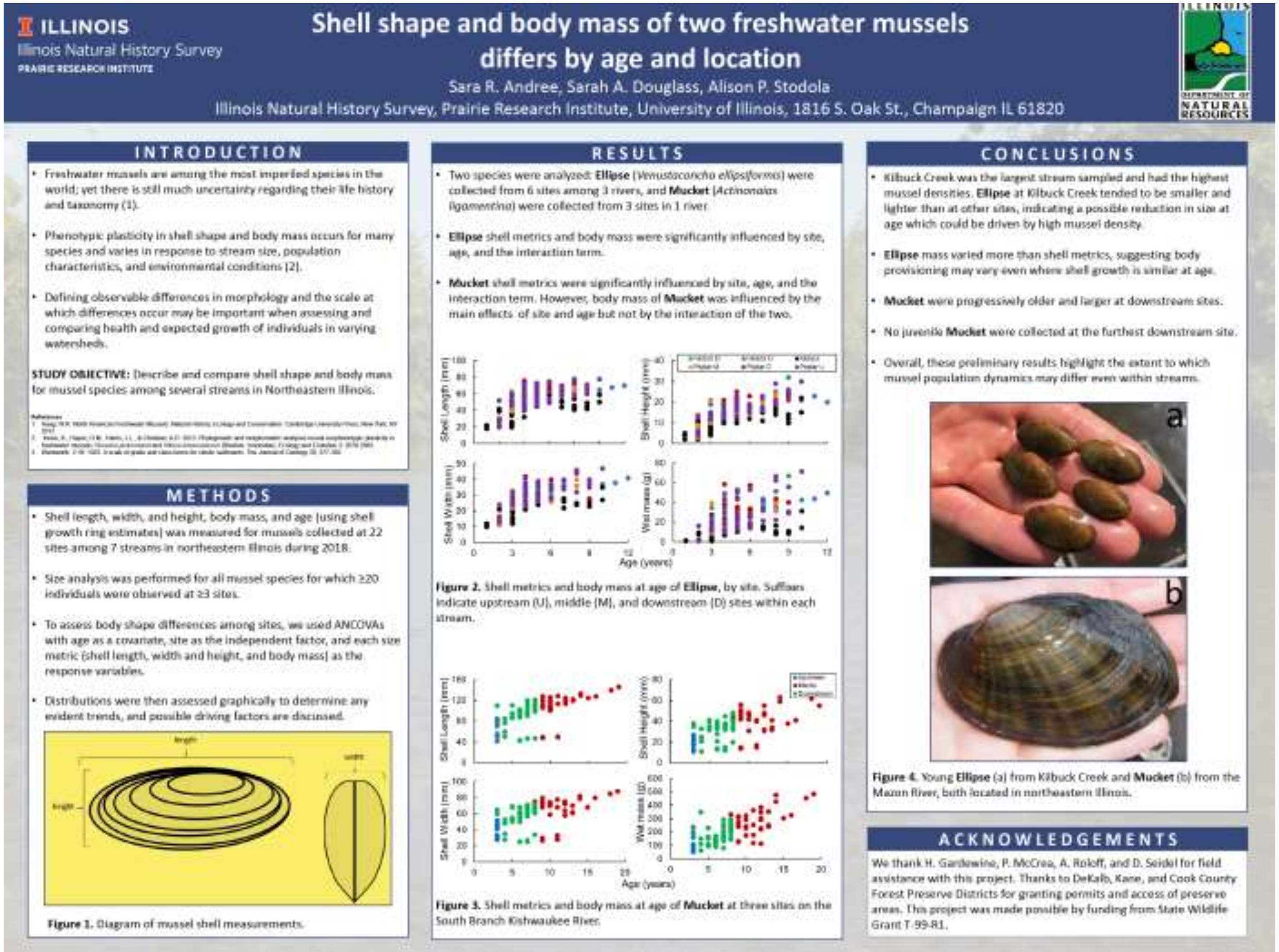
<u>Overview</u>

The Illinois Nutrient Loss Reduction Strategy (NLRS) is a living document which details several plans around the state, and is coordinated by numerous agencies, landowners, and public interest groups. It aims to reduce primarily nitrogen and phosphorus inputs to waterbodies in the upper Mississippi River watershed, which are the leading contributor to widespread hypoxia in the Gulf of Mexico (Alexander et al. 2008; NLRS 2019). Along with this effort, many effects of nutrient reduction in priority watersheds throughout Illinois are being monitored, including effects of nutrient management practice changes on freshwater mussel communities (NLRS 2019). To this end, the Illinois Natural History Survey has created a conceptual model for monitoring of mussel community richness in the Embarras and Vermilion-Wabash drainages of eastern Illinois using a Bayesian Belief Network (BBN; Figure 1; see Andree et al. 2019 for more detail). This network allows for flexible addition of nodes and structural changes as monitoring continues and allows managers to predict the likelihood of species loss under specific scenarios. Empirical data were included for all nodes for which they were available. For nodes where no empirical data were available, a literature survey was conducted to estimate node state probabilities based on prior knowledge. Where no estimate could be made, uniform probability distributions were used as placeholders. Overall, the aim of this conceptual BBN is to provide a starting point for evaluating the health of impaired watersheds in Illinois with respect to freshwater mussel community richness as predicted by a suite of potentially important variables. A summary of variables included in the model, a brief description of their relationship to mussel community richness, and a description of how each node was populated is presented below.

<u>Target Areas</u>

We investigated the Embarras River and Vermillion- Wabash River drainages as regions to consider restoration efforts for species richness, rather than a single species restoration. These drainages were selected because they are target watersheds for Illinois' Nutrient Loss Reduction Strategy, which may have impacts on future freshwater mussel richness. After contacting several USDA-NRCS members, we were able to obtain a map of projects in Vermilion County, and general discussions of the conditions of target watersheds. The Vermilion-Wabash River area has undergone a significant amount of land use improvement, largely through the creation of riparian buffers and changes in tillage practices. Conversely, officials reported little change in the Embarras River area. We further narrowed our focus based on the ability to sample several sites within a river and sampled 9 sites each on the Salt Fork Vermilion and Embarras Rivers.

Appendix IX: Freshwater Mollusk Conservation Society poster in San Antonio, Texas - Andree, S., S. Douglass, and A. Stodola. 2020. Shell shape and body mass of two freshwater mussels differ by age and location.



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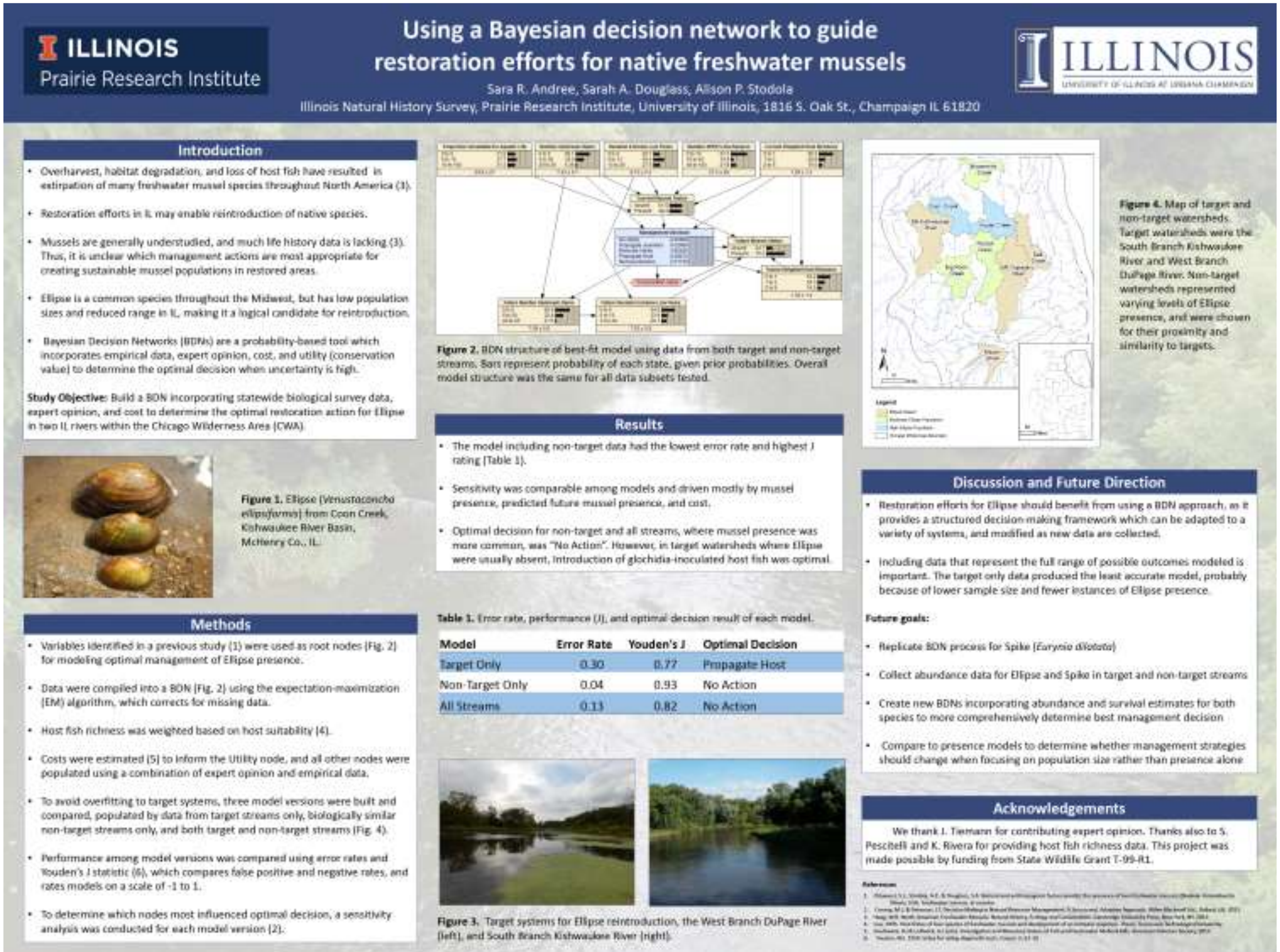

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