Hierarchical Landscape Models for Endemic Unionid Mussels: Building Strategic Habitat Conservation Tools for Mussel Recovery in the South Atlantic Landscape Conservation Cooperative

Interim Annual Progress Report for the Period
October 1, 2010 through September 30, 2011

Submitted to
U.S. Fish and Wildlife Service
South Atlantic Landscape Conservation Cooperative
Raleigh, NC 27606

by

Thomas J. Kwak, W, Gregory Cope, C. Ashton Drew*

NC Cooperative Fish and Wildlife Research Unit
North Carolina State University
Department of Biology
Raleigh, NC 27695-7617

and

Tom Augspurger
U.S. Fish and Wildlife Service
Raleigh Field Office
Raleigh, NC 27635

*Author contact: Ashton Drew, cadrew@ncsu.edu, 919-513-0506

Abstract

This report summarizes progress toward developing the hierarchical modeling framework to predict habitat suitability and occupancy of unionid mussels. Our case study for the model framework development and validation is the Tar River spinymussel (TRSM, *Elliptio steinstansana*) in the Tar and Neuse river basins. In the past six months, we have led a design workshop, collected and commenced evaluation of GIS data resources, drafted the Bayesian belief network (BBN) model structures, and designed an interview template with associated statistical methods. We outline the methods and results (or current status) of each of these steps. Work remaining includes: solicit external review of the proposed BBNs and interview script, conduct interviews, process expert knowledge through statistical software to parameterize models, run the models to spatially predict habitat of low, medium, or high suitability, and conduct field sampling to validate and update the habitat models while simultaneously predicting occupancy.

Project Background and Objectives

The Southeastern US supports high diversity of freshwater mussels; however, many of these species are in decline. Impacts from multiple sources, including land use change, conflicting water resource demands, and pollution, have placed many species on the threatened and endangered list. Furthermore, changing temperature and precipitation patterns attributed to climate change are altering the aquatic landscape such that habitat suitable in the present may not be suitable in the future. The USFWS, together with partnering agencies through the South Atlantic Landscape Conservation Cooperative (SALCC), has requested a model that will support mussel population recovery and habitat management efforts within an adaptive management framework. Specifically, the model should characterize streams reaches in a manner that supports prioritizing among the following decisions: do nothing, protect habitat of existing population, restore habitat, translocate individuals, or release captive bred individuals (Figure 1).

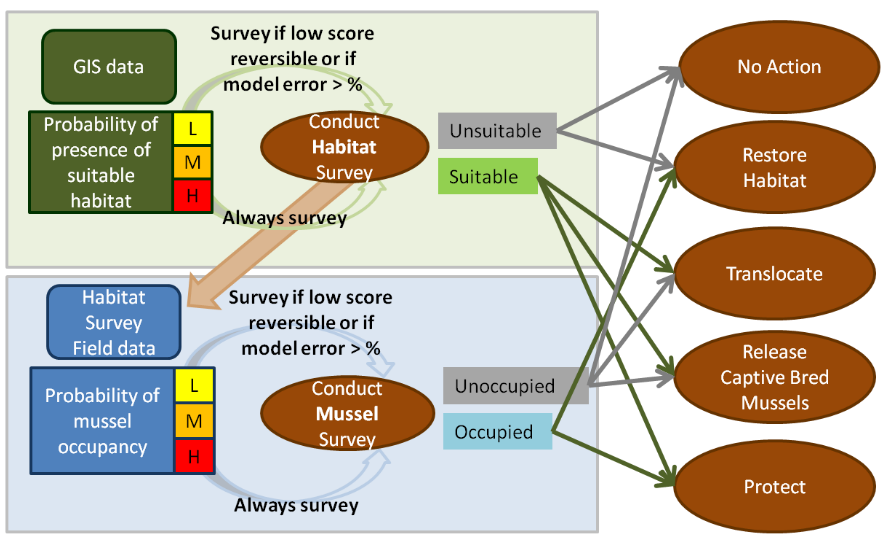

Fig 1. Illustration of hierarchical model design to support mussel population recovery and adaptive management. A landscape-scale BBN model (green boxes) uses GIS data to predict for low, moderate, or high probability of suitable habitat. A site-scale BBN model (blue boxes) uses field data to predict for low, moderate, and high probability of TRSM occupancy. The models could be used to guide decisions (brown ovals) about monitoring (when and where to conduct surveys) and management (when, where, and what actions to take). All data collected support decisions in the present, but also update the models through a learning process, so that what begin as expert-based models gradually update to data-driven decision support tools.

Design Workshop

We hosted a two-day workshop in June 2011 to elicit knowledge from experts of Tar River spinymussel biology/ecology and habitat associations and landscape-scale processes that shape stream habitat conditions (hydrology, chemistry, and geomorphology). The purpose was to identify the data resources (empirical data, GIS data, and expert knowledge) available to parameterize a hierarchical model that first predicts probability of suitable habitat based on regional landscape (GIS) data and then predicts the probability of occupancy by mussels and their fish hosts based on empirical data measured on-site. Information gathered through the workshop informs the selection of elicitation method and statistical analysis techniques that serve as the foundation for rigorous expert-based models. Thus, the goal was not to reach consensus decisions, but rather to fully explore the diversity of decisions proposed and understand the existing and required knowledge underlying each proposal.

The sixteen workshop participants (Appendix 1) represented federal, state, and private agencies with knowledge of mussel biology/ecology and/or stream geomorphology. All participants completed a knowledge survey form, in which they self-assessed their knowledge of specific topics and their experience working at multiple temporal and spatial scales (Appendix 2, available upon request). This survey allows us to assess strengths and gaps in participants' knowledge. The results will be referenced when building and assessing the expert-based models, but will not be used to weight individuals' contributions.

Past workshops with mussel experts have elicited valuable qualitative information about microhabitat characteristics associated with healthy mussel populations (TRSM 2009 Sanctuary Workshop draft materials, T. Augspurger and S. McRae, USFWS, R.Nichols, NCWRC). However, obtaining quantitatively defined species-habitat associations has proved challenging, especially at landscape scales. By extending the invitation to non-mussel experts knowledgeable of the landscape-scale physical processes that shape stream habitats, we hoped to initiate dialog that would draw clearer linkages between mussel experts' microhabitat knowledge and the available GIS data (including metrics that could be derived from existing data layers).

Following welcoming comments (T. Kwak, USGS), the workshop began with a series of presentations from selected participants. These presentations introduced the current project relative to ongoing TRSM recovery and management activities (T. Augspurger, USFWS; A. Drew, NCSU) and reviewed other ongoing TRSM-inclusive research and modeling projects (T. Pandolfo, NCSU; K. Montieth, The Catena Group). M. Doyle (UNC) provided an overview of his research in the field of river science and policy relevant to water quality, sediment transport, and channel development. C. Goudreau (NCWRC) summarized state agency efforts to understand and conserve aquatic habitats for mussels and other aquatic species.

Workshop participants then the proceeded through a series of small-group and large-group discussions to (1) define the project scope, (2) describe site-scale field conditions and assessment methods, (3) identify GIS data available to represent these site-level conditions, and (4) clarify the relationship between TRSM and two associated mussel species. Notes from the group discussions appear in Appendix 2 (available upon request). Results are incorporated into the descriptions of draft model products below.

Bayesian Belief Network Model

Bayesian Belief Networks **(**BBNs) support adaptive management of complex systems (Nyberg et al. 2006), because they share the same conceptual foundation of continuous, incremental learning. BBNs provide a framework for that learning by (1) forcing explicit, quantitative statement of hypotheses that underlie decision processes, (2) visually communicating relationships among key system drivers and response variables, (3) incorporating uncertainty into model predictions, and (4) providing diagnostic tools to guide the monitoring and learning processes. The TRSM BBNs will be constructed primarily from expert-knowledge, supplemented by literature review and unpublished empirical data available for some variables. Our procedure to construct the models includes several cycles of knowledge elicitation, model development, and model review (Figure 2). Through this process, we use a variety of tools to gradually move from eliciting qualitative information to eliciting quantitative information.

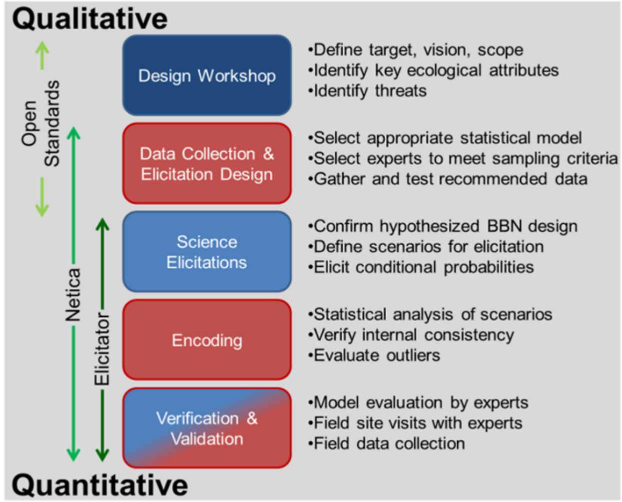

Fig 2. Graphical representation of the project workflow. Through these five steps, we must move from expert statements of qualitative species-habitat relationships to quantitative hypotheses. Blue boxes indicate steps requiring expert-knowledge elicitation, while red boxes indicate steps performed by the modeler. The arrows on the left indicate our primary elicitation and expert-knowledge analysis tools.

<u>Variables Defined in Open Standards Design Workshop</u>

Our initial data organization and elicitation methods drew heavily from the Open Standards for the Practice of Conservation (Conservation Measures Partnership 2007). The Open Standards is a procedural framework created to help natural resource managers define, set, and assess conservation objectives. We used the Open Standards terminology (Table 1) to define project components (target, scope: Table 1) and to identify critical components of the TRSM ecological system (key ecological attributes and threats: Tables 2 and 3). However, the Open Standards, and its associated software Miradi, are not statistical tools to predict probabilistic outcomes with associated uncertainties. Also, the Open Standards is designed to identify and manage threats to conservation targets, while our models aim to quantitatively define and predict the location of conservation targets. Therefore, after eliciting the basic

Table 1. Terms from the Open Standards methodology were employed in the design workshop and throughout this document.

Term	Open Standards Definition	Workshop Outcome
Scope	• The thematic focus or geographic area of a project in which to concentrate efforts.	• Tar and Neuse River basins upstream from the limit of the salt water wedge
Target	• Specific species, ecological systems/habitats, or ecological processes around which a project is focused	• Suitable habitat occupied by reproductively active TRSM
Threats	• An anthropogenic activity that may cause the destruction, degradation, and/or impairment of biodiversity and natural processes	• See Table 2
Key ecological attributes	• The characteristics of or elements required by a target central to its success	• See Table 3

qualitative information at the design workshop (materials currently in review), we transferred this information to the BBN modeling software Netica (version 4.08, Norsys Systems Corp., Vancouver, BC, Canada).

<u>Model Framework Constructed in Netica</u>

In Netica, we are constructing the influence diagrams (also referred to as causal networks or belief networks) which depict relationships among key ecological attributes, threats, and targets (Figure 3). BBNs represent variables and their interactions as nodes connected by directed links (Marcot et al. 2006; Nyberg et al. 2006). Parent nodes lead into child nodes, and there can be multiple steps from the initial input nodes (predictor variables) through intermediate nodes (latent variables) to the final output node (response variable). All nodes assign data, whether empirical or calculated, into categorical states. Defining appropriate states requires careful consideration of the available data, expected future sampling effort, and project objectives (Kuhnert and Hayes 2009). Conditional probabilities for the states of each child node must be specified for all combinations of states of their parent nodes. These conditional probabilities can be specified by learning algorithms, based on case data, by equations defined by the modeler, or by asking experts to complete the conditional probability tables directly. If probabilities will be elicited from experts, then two BBN design constraints are recommended (Marcot et al. 2006): (1) no child should have more than three parents and (2) no parent node should have more than five states. Following these recommendations we are creating two BBN models, the first to predict the probability of suitable habitat based on data input from GIS data, and the second to predict the probability of occupancy based on data input from field surveys. The first of these draft model influence diagrams is currently in review, while the second is in development.

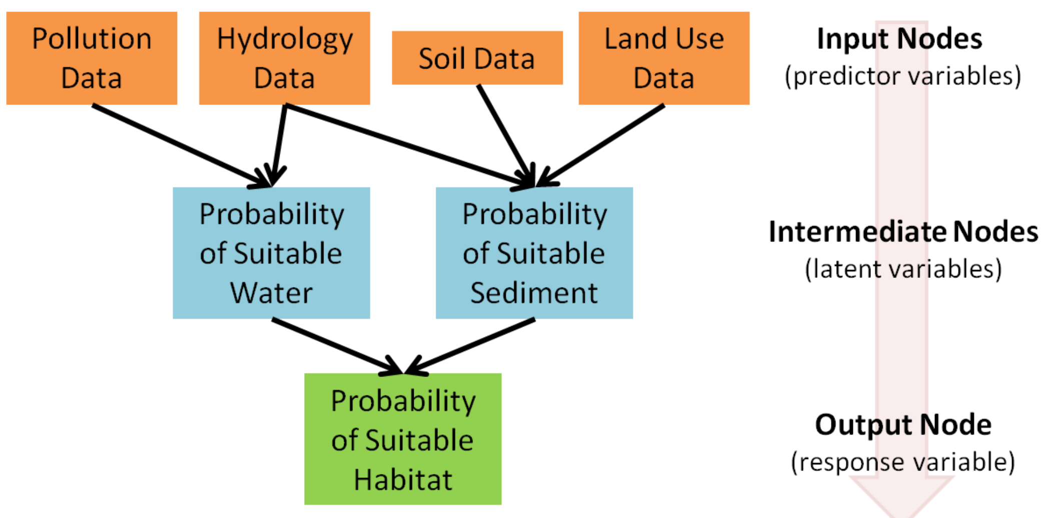

Fig 2. A stylized example of an influence diagram.

<u>Probability Elicitation in Elicitator</u>

Once the BBN model influence diagrams have been defined, we will use the software application Elicitator (James et al. 2010) to design and conduct interviews that independently capture, encode, and then combine each expert's probability estimates. The indirect, scenario-based elicitation techniques supported by Elicitator (Low-Choy et al. 2010) counter some of the common errors and biases (Kynn 2008) encountered during expert elicitation. In addition, by using an approach similar to a latin-square experimental design, Elicitator identifies the minimum number of questions necessary to elicit relationships among all variables (Low-Choy et al. In Press). This greatly reduces the elicitation burden on the expert to fill every value in a conditional probability table in Netica, and thereby relaxes the need to restrict the parent-to-child node ratio. Finally, Elicitator quantifies the variability and uncertainty in each expert's responses, to more accurately reflect the precision of their knowledge and ultimately to better reflect the uncertainty inherent to model predictions. As the elicitation is conducted, tabular and graphical results are generated instantly (Low-Choy et al. 2010), allowing the expert to review the products of their answers and correct any immediate errors. The probability distributions calculated from experts' combined knowledge are transferred back into Netica as equations to fill the conditional probability tables.

Key Ecological Attributes, Threats, and their Proxy GIS Data Sources

Our workshop discussions identified many qualitative clues that experts use to distinguish between sites with high versus low potential to support healthy mussel populations. Participants also discussed the challenges associated with legacy effects (Harding et al. 1998), acute versus chronic effects, the apparent absence of reproduction in extant TRSM sites, and the associated challenges of inferring habitat suitability from presence/absence observations. Both within the workshop and later through supplemental literature review, we worked to distinguish major themes by which to group expert inferences and to match the qualitative clues to associated empirical field and GIS measures. To sort information, we considered whether the clues related to (1) physical, chemical, or biological features, (2) natural potential versus anthropogenic stresses, and (3) local versus landscape scale processes.

The results of this thematic sorting for the habitat suitability BBN are presented in Tables 2 and 3. While the designation of such thematic groups is always somewhat subjective, it is not arbitrary. Five related factors informed our deliberations: (1) the objective to ultimately apply the information to adaptive management problems, (2) the design constraints of BBN models, (3) the elicitation endurance limits of experts who would have to quantify linkages among variables, (4) the quality and coverage of available GIS data, and (5) the effort and financial limits of what empirical data can reasonably be collected in the field. Based on these criteria, we identified five key ecological attributes of suitable habitat (water, thermal buffer, substrate, hydrologic refugia, chemistry) and five threats that potentially impact one or more of the key ecological attributes (eutrophication, chemical pollution, thermal stress, flashy hydrology, impeded or reduced flow, siltation).

Relationships between the key ecological attribute, threats, field measures, and GIS proxy data illustrated in Tables 2 and 3 are currently in review. The review instructions (available upon request) provide some further background to interpretation of the tables and these relationships. Briefly however, we began with a qualitative statement describing a characteristic of "good" mussel habitat, such as "water must be available year round". Then, given that mussel and mussel habitat surveys are typically conducted by single visits in summer, we asked how experts infer the presence of year-round adequate water during that one visit. We allowed up to three field measurements to be named. In the next round of interviews, experts will quantify which values for that measure (along a scale representing all possible values present in the Tar and

Neuse river basins) would lead them to infer a high, moderate, or low probability of the presence of suitable water levels. These are the measurements that we must have to predict with proxy GIS data via the BBN habitat suitability model and that we will measure to validate (and update) the models in summer 2012.

Table 2. Five key ecological attributes (KEA) with their associated definitions, proxy data, and field measurements. The proxy data variables will predict for the quantitative measures, allowing inference about the suitability of the habitat as the product of the expected suitability of each KEA.

VARIABLE NAME **Key Ecological Attribute (KEA)**	**DEFINITIONS** **How does a mussel expert recognize a site where these KEAs are present?** ***Qualitative definition*** • **Quantitative definition**	**PROXY DATA** **What landscape data inform the probability of presence of these KEAs?** ***Proxy spatial data resource*** • **Proxy spatial data variable**	**FIELD DATA** **What data is collected in the field to verify the presence of these KEAs?**
Water	*Water is available year-round to deliver food and oxygen.* • Wetted width at base flow ≥ ___. • Water depth at base flow ≥ ___.	*WaterFALL* • Minimum annual wetted width (m) • Groundwater contribution (units?) • Max consecutive days at 0m water depth (count/year)	• Base flow wetted width (m) • Base flow depth (m) • Discharge gauge data (cu.ft/sec) • Channel vegetation (p/a)
Thermal Buffer	*Temperature extremes are buffered.* • Temperatures between ____ and ____ at base flow. • Densiometer reading ≥ ___.	*LIDAR* • Canopy closure • Irradiance value (?) *WaterFALL* • Groundwater contribution (units?)	• Thermometer (°C) • Canopy closure (densiometer) • Temperature logger, daily min/max (°C)
Substrate	Stable substrate is solid enough to support mussels, but soft enough to allow burrowing. • Streambed substrate dominated (> ____%) by sand/pea gravel mix. • Fine silt/clay content is less than ____.	*SSURGO* • Sand content • Silt/Clay content • Organic Matter content *WaterFALL* • Average annual discharge (?)	• Compaction (penetrometer) • Substrate sediment size (D84/D50/D16) • Bank stability (p/a of vegetation?)
Hydraulic Refugia	*In-stream structure modifies flow to create diverse microhabitats.* • Rock outcroppings and/or woody debris are present in the stream channel. • Pool/riffle/run structure is present in the stream channel.	*SEGAP* • % Forested riparian *Geology* • Surficial geology *WaterFALL* • Slope (?) • Channel type (?)	• Established woody debris (p/a) • Pool/riffle/run sequences (count) • Channel complexity (?) • Large boulders or bedrock (p/a)
Chemistry	*Water chemistry supports growth and reproduction.* • Specific conductivity above _____. • pH value between ____ and ____.	*SSURGO* • Calcium Carbonate content • Cation exchange capacity	• Specific conductivity • pH • Hardness (Ca^{2+}, Mg^{2+})

Table 3. Six threats with their associated impacted key ecological attributes, definitions, proxy data, and field measurements. The proxy data variables will predict for the quantitative measures, allowing inference about the suitability of the habitat as the product of the expected suitability of each KEA.

VARIABLE NAME **Threat** • Primary causes	**KEA IMPACTED** • Water • Thermal Buffer • Substrate • Hydraulic Refugia • Chemistry	**DEFINITIONS** **How does a mussel expert recognize a site where these threats are present?** ***Qualitative definition*** • **Quantitative definition**	**PROXY DATA** **What landscape data inform the probability of presence of these threats?** ***Proxy spatial data resource*** • **Proxy spatial data variable**	**FIELD DATA** **What data is collected in the field to verify the presence of these threats?**
Eutrophication • Fertilizers • Sewage • Animal waste	Chemistry	Increased N and P introduced to the water accelerates plant growth and depletes oxygen needed for respiration. • Dissolved oxygen at base flow ≤___.	*STORET* • Point source outfalls *SEGAP* • % agriculture & plantation • % suburban *EPA* • Impaired waters	• Dissolved oxygen (mg/L) • Heavy algal growth (p/a)
Toxicants • Industrial effluents • Sewage • Mines • Roads	Chemistry	Stressful or lethal chemicals introduced to the water impair growth, maturation, and /or respiration. • pH (?)	*STORET* • Impaired waters • Point source outfalls *SEGAP* • % impervious *NC DOT* • Road crossings	**There are no direct field measures for most toxic chemicals (heavy metals, endocrine disrupters, hydrocarbons, ammonia, etc). Instead water samples must be collected and sent for testing for specific chemicals.*
Thermal Stress • Shading canopy removed • Point source thermal effluent	Thermal Buffer Chemistry	Extreme and/or extended periods of high temperatures cause physical stress and reduce oxygen availability. • Water temperature at base flow ≥ ____ . • Sediment temperature at____ depth at base flow ≥ ____. • Dissolved oxygen at base flow ≤ ____.	*LIDAR* • Irradiance value (?) • Canopy closure *WaterFALL* • Groundwater contribution *STORET* • Thermal effluent outfalls	• Water temperature (°C) • Sediment temperature profile (°C) • Canopy closure (densiometer) • Dissolved oxygen (mg/L) • Water depth at base flow (m)

Table 3. Threats continued.

VARIABLE NAME Threat • Primary causes	KEA IMPACTED • Water • Thermal Buffer • Substrate • Hydraulic Refugia • Chemistry	DEFINITIONS How does a mussel expert recognize a site where these threats are present? *Qualitative definition* • Quantitative definition	PROXY DATA What landscape data inform the probability of presence of these threats? *Proxy spatial data resource* • Proxy spatial data variable	FIELD DATA What data is collected in the field to verify the presence of these threats?
Flashy Hydrology • Dams • Increased, accelerated runoff	Water Substrate Hydraulic Refugia	Highly variable flow with extremes and rate of change outside natural flow conditions destabilize stream substrate and structure. • Recent bank scour and destabilization evident. • Significant woody debris recently deposited.	*SEGAP* • % impervious • % hardwood forest • % wetland *NC DWQ?* • Dams	• Channel instability (scour p/a) • Established vegetation (p/a) • Recent woody debris (p/a) • Stream gauge
Impeded or Reduced Flow • Blocked flows • Water withdrawal	Water	Extended low flow conditions result in dry stream bed. • Dry at base flow • Dead, desiccated vegetation in stream bed.	*NC DOT* • Crossings/Culverts *SEGAP* • % pine plantation *STORET(?)* • Withdrawal permits (?)	• Stream gauge • Presence established vegetation
Siltation • Land clearing and developme nt	Substrate Hydraulic Refugia	Increased delivery of sediments to stream reduces visibility and/or smother mussels. • Turbidity under base flow conditions exceeds _____. • Deposition rates exceed _____.	*SEGAP* • % forest in riparian • % agriculture in riparian *SSURGO* • Kw erosion factor	• Bank erosion • Presence riparian vegetation • D50/D85 • Sediment composition • Secchi disk or other turbidity measure

Workshop participants recommended many potential GIS data and database resources. From these, we selected one set to serve as proxy data for generating spatial predictions and a second set to provide preliminary training and ground-truthing of our models. Proxy data resources were matched to each key ecological attribute and threat (Tables 3 and 4). At present, we anticipate pulling data from eight GIS datasets: USGS Southeast Gap Analysis Program data (SEGAP), NC Light Detection and Ranging data (LIDAR), NRCS Soil Survey Geographic database (SSURGO), NCDWQ Ambient Monitoring System data from the USEPA Storage and Retrieval system (STORET), RTI Watershed Flow and Allocation Modeling System Using NHDplus (WaterFALL™), NC Department of Transportation data (NCDOT), NC Center for

Geographic Information and Analysis (NCCGIA), and the NC State Geology map data (Geology).

We have obtained most of these data layers (RTI data acquisition pending) and are currently: (1) evaluating their metadata to ascertain spatial and temporal relevance, (2) contacting source agencies to confirm we have the most recent version and most appropriate product, and (3) generating scope-wide summary statistics to determine what spatial scales offer the greatest opportunity to discern differences among streams within our scope. For this third task, each 500-meter stream segment in the Tar and Neuse river basins is currently being attributed with data across various scales. These scales include individual stream catchments, USGS 14-digit HUCs, and entire upstream watersheds. Thus far, we have been working with the data for land use/land cover, underlying bedrock, soil type, species presence, and point source discharges. Further physical attributes will be calculated and added to the GIS database as the spatial data layers become available. The resulting database will serve as input values for the habitat suitability BBN model.

To assist in structuring the models and selecting appropriate scales to represent the GIS data, we are reviewing selected publications that define correlative relationships between GIS data and mussel presence, abundance, or richness (e.g., Andersen 2002, Arbuckle and Downing 2002, Gangloff and Feminella 2007, McRae et al 2004). We are also reading publications that review correlative relations between land use patterns and stream microhabitat conditions (e.g. Liu et al. 2000, Moore et al. 2005). Although these correlative studies do not readily transfer to new spatial settings, they collectively provide valuable insight into potential patterns and processes that we should consider.

Next Steps and Overall Status Assessment

Our immediate next step is to complete the construction of the landscape-scale habitat suitability BBN model. To complete design of the scenarios in Elicitator, we must first (1) address any corrections or concerns raised in revision of the proposed key ecological attributes and threats materials, (2) use the summary data extracted from each proxy GIS data layer to define appropriate categorical states for each predictor variable (input node), (3) use the latin-square approach to design the minimum set of elicitation scenarios, and (4) test the survey by piloting it with an independent mussel expert and reviewing the results with a statistician. These steps are necessary to ensure that the elicitation design meets standards for scientific rigor and repeatability (Perera et al. In Press).

Design of the site-scale TRSM occupancy BBN will be accomplished in close cooperation with the related mussel occupancy modeling research of T. Pandolfo, a Ph.D. student at NC State University, who is conducting TRSM research as part of a USGS funded climate change project in the Tar River Basin of NC. In basic terms, the occupancy BBN model simply substitutes the input GIS variables for input field variables and then adds additional variables to address the biological suitability of a given site (e.g., presence of host fish and associated mussel species). However, Pandolfo's research will likely provide information useful to propose more informative categorical states for certain variables, or even the removal of some variables. Finally, if she is able to identify strong correlations between certain field measures and TRSM (or closely-related species) occupancy, this would remove the necessity to include these questions in the expert interviews, while if she identifies complex interactions, this would lead us to pose additional questions. For these reasons, we will first complete the landscape-scale habitat suitability BBN model, and then proceed with both occupancy models simultaneously.

The work is proceeding at a steady pace according to schedule, and we anticipate completing the draft habitat suitability BBN by December 2011 and the draft occupancy BBN by March 2012. Therefore, we are on schedule to have the final habitat suitability BBN model completed to propose additional sampling sites in 2012, so we can then validate and update the model, as proposed.

References

Andersen EF (2002) Effects of land use and land cover on freshwater mussel populations in the upper Neuse River basin, NC: a GIS approach. MS Thesis, North Carolina State University, Raleigh, NC

Arbuckle KE, Downing JA (2002) Freshwater mussel abundance and species richness: GIS relationships with watershed land use and geology. Canadian Journal of Fisheries and Aquatic Science 59:310-316

Conservation Measures Partnership (2007) Open Standards for the Practice of Conservation, Version 2.0, October 2007. [online] http://www.conservationmeasures.org/wp-content/uploads/2010/04/CMP_Open_Standards_Version_2.0.pdf

Gangloff MM, Feminella JW (2007) Stream channel geomorphology influences mussel abundance in southern Appalachian streams, USA. Freshwater Biology 52:64-74

Harding JS, Benfield EF, Bolstad PV, Helfman GS, Jones III EBD (1998) Stream biodiversity: the ghost of land use past. Proceedings of the National Academy of Sciences USA 95:14843-14847

James A, Low-Choy S, Mengersen K (2009) Elicitator: a software-based expert knowledge elicitation tool for regression in ecology. Environmental Modelling Software 25:129–145

Kuhnert PM, Hayes KR (2009) How believable is your BBN? In: Anderssen RS, Braddock RD, Newham LTH (eds) 18th World IMACS/MODSIM Congress, Cairns, Australia, 13–17 July 2009, Modelling and Simulation Society of Australia and New Zealand, Cairns, pp 4319–4325. Available from http://mssanz.org.au/modsim09 (accessed May 2011)

Kynn M (2008) The ‘heuristics and biases’ bias in expert elicitation. J Roy Stat Soc Series A 71(1):239–264

Liu Z, Weller DE, Correll DL, Jordan TE (2000) Effects of land cover and geology on stream chemistry in watersheds of Chesapeake Bay. Journal of the American Water Resources Association 36:1349-1365

Low-Choy S, Murray J, James A, Mengersen K (In Press) Elicitator: a user-friendly, interactive tool to support scenario-based elicitation of expert knowledge. In: Perera A, Drew CA, Johnson C (eds) Expert Knowledge and its Application in Landscape Ecology. Springer, New York

Low-Choy S, Murray J, James A, Mengersen K (2010) Indirect elicitation from ecological experts: from methods and software to habitat modelling and rock-wallabies. In: O'Hagan A, West M (eds) Oxford Handbook of Applied Bayesian Analysis. Oxford University Press, Oxford

Marcot BG, Steventon JD, Sutherland GD, McCann RK (2006) Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. Canadian Journal of Forest Research 36: 3063-3074

McRae SE, Allan JD, Burch JB (2004) Reach- and catchment-scale determinants of the distribution of freshwater mussels (Bivalvia: Unionidae) in south-eastern Michigan, USA. Freshwater Biology 49:127-142

Moore RD, Spittlehouse DL, Story A (2005) Riparian microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resources Association 41:813-834

Nyberg JB, Marcot BG, Sulyma R (2006) Using Bayesian belief networks in adaptive management. Canadian Journal of Forest Research 36: 3104-3116

Perera AH, Drew CA, Johnson CJ (eds) (In Press) Expert Knowledge and its Application in Landscape Ecology. Springer, New York

Appendix 1. Participants attending the Tar River Spiny Mussel Habitat Suitability and Occupancy Workshop, June 8 & 9, 2011, in Raleigh, North Carolina.

Tom Augspurger
Aquatic Toxicologist
US Fish and Wildlife Service
Raleigh, NC
919-856-4520, X 21
tom_augspurger@fws.gov

Greg Cope
Aquatic Toxicologist
NCSU Department of Environmental & Molecular Toxicology
Raleigh, NC
919-515-5296
greg_cope@ncsu.edu

Tom Dickenson
Aquatic Biologist
The Catena Group
Hillsborough, NC
tdickinson@thecatenagroup.com

Martin Doyle
River hydrology and engineering
UNC Department of Geography
Chapel Hill, NC
919-962-3876
mwdoyle@email.unc.edu

Chris Eads
Aquatic Animal Epidemiology and Conservation Genomics Laboratory
NCSU Veterinary School
Raleigh, NC
919-513-6655
Chris_Eads@ncsu.edu

John Fridell
Aquatic Biologist, SE Regional Aquatics Team
US Fish and Wildlife Service
Asheville, NC
828-258-3939 x225
john_fridell@fws.gov

Chris Goudreau
Special Projects Coordinator
NC Wildlife Resources Commission
828-659-3324 x223
chris.goudreau@ncwildlife.org

Tom Kwak
Aquatic Biology
USGS NC Cooperative Fish & Wildlife Research Unit
NCSU Department of Biology
Raleigh, NC
919-513-2696
tkwak@ncsu.edu

Sarah McRae
Aquatic Ecologist
US Fish and Wildlife Service
Raleigh, NC
919-856-4520, ext. 16
sarah_mcrae@fws.gov

Kate Monteith
GIS Technician
The Catena Group
Hillsborough, NC
919-732-1300
kmonteith@thecatenagroup.com

Rob Nichols
Eastern Aquatic Wildlife Diversity Coordinator
NC Wildlife Resources Commission
Raleigh, NC
919-896-6254
rob.nichols@ncwildlife.org

Tamara Pandolfo
Graduate Student
NCSU Department of Biology
Raleigh, NC

Judy Ratcliffe
Eastern Region Freshwater Ecologist
NC Natural Heritage Program
Raleigh, NC
919-715-7807
judith.ratcliffe@ncdenr.gov

Tim Savidge
Aquatic Biologist
The Catena Group
Hillsborough, NC
o: 919-732-1300
c: 919-417-2314
tsavidge@thecatenagroup.com

Fred Tarver
Aquatic Ecologist
NC Department of Environment and Natural Resources
Division of Water Resources
919-715-5442
fred.tarver@ncdenr.gov

Brian Watson
Aquatic Ecologist
VA Department of Game and Inland Fisheries
434-525-7522
Brian.Watson@dgif.virginia.gov

Rua Mordicai (Observer)
Science Coordinator
South Atlantic Landscape Conservation Cooperative
US Fish and Wildlife Service
Raleigh, NC
919.707.0122
rua@southatlanticlcc.org

Ashton Drew (Facilitator)
Coordinator, Environmental Decision Analysis
NC Cooperative Fish and Wildlife Research Unit
Biodiversity and Spatial Information Center
NCSU Department of Biology
Raleigh, NC
919-513-0506
cadrew@ncsu.edu

Louise Alexander (Facilitator)
Research Assistant, Environmental Decision Analysis
NC Cooperative Fish and Wildlife Research Unit
Biodiversity and Spatial Information Center
NCSU Department of Biology
Raleigh, NC
919-513-7337
louise_alexander@ncsu.edu