Brook Floater restoration: identifying locations to reintroduce or augment populations with propagated mussels

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Brook Floater Restoration: Identifying Locations to Reintroduce or Augment Populations with Propagated Mussels

A Case Study from the Structured Decision Making Workshop
3-7 February 2020
Massachusetts Division of Fisheries and Wildlife, Westborough, MA

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Decision Problem

Brook floater (*Alasmidonta varicosa*) is a stream-dwelling freshwater mussel that has experienced significant reductions in the number of populations (occupied locations) throughout its range and is listed as a species of conservation concern in all states in the United States and two Canadian provinces where it is currently found. However, the magnitude of population loss and knowledge of population status is highly variable across locations, leaving states and provinces with uncertainty about the most effective recovery plan. Moreover, in locations where population restoration via reintroduction or augmentation with lab-propagated mussels has been identified as an important component of recovery, there are questions about the number and location of restoration sites. In February 2020, we held a workshop where we sought to identify where states should reintroduce or augment brook floater to minimize the probability of extinction within a state. We focused on Massachusetts and Connecticut, two states with only a few, small populations still extant, that likely need population restoration to prevent statewide extirpation. Workshop participants included three state decision makers (JC, PH, LS), a mussel biologist from a non-focal state (MK), and three researchers (AHR, DP, AS). The workshop was facilitated by an overall coach (RK) and three project-specific coaches (EB, JC, KK) and coordinated by CCC. We identified that restoration actions aimed at redundancy (number of populations), representation (number of occupied basins), and resiliency (population size) were constrained by resource availability such as limited broodstock, staff time, and budgets. Optimal restoration locations depended on habitat conditions, the status (viability) of nearby mussel populations, population size (number of individuals), and the location within watersheds; all important considerations in addressing population persistence. Restoration actions also

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accounted for the risk of disease transmission among mussels and fish, and the genetic health and diversity of mussel populations. The workshop identified the multiple, compounding uncertainties related to population restoration, identified information gaps critical to decision making, and charted a path forward to make decisions given uncertainties. The optimization approach developed can be used to select specific watersheds for restoration in any state, province, or region and can easily be adapted as new information becomes available.

Background

Legal, regulatory, and political context

The brook floater (*Alasmidonta varicosa*) has been extirpated in Rhode Island and Delaware and is listed as a species of greatest conservation need (SGCN) in the 14 states where it is currently found from Georgia to Maine in the United States (U.S.), and in two Canadian provinces, New Brunswick and Nova Scotia (Wicklow et al. 2017). Following a Species Status Assessment (SSA) conducted in 2018 (USFWS 2018), the U.S. Fish and Wildlife Service (USFWS) decided that the brook floater did not warrant listing under the federal Endangered Species Act (USFWS 2019). This decision was made in part due to the ongoing, coordinated research and conservation conducted by the Brook Floater Working Group (BFWG). The BFWG, which was formed as part of a multi-state USFWS State Wildlife Grant awarded in 2016, has created opportunities for shared resources, learning, and conservation across the species' range. While states are responsible for assessing populations, developing restoration actions, and preventing local extirpation within their jurisdiction, regional coordination is critical to protecting the species throughout their range.

Propagation and reintroduction or augmentation of populations has been identified as an important conservation strategy for restoring brook floater. Such actions are often considered a last resort measure when population sizes are critically small (thus minimizing opportunities for natural reproduction) and threats causing initial population declines have been mitigated (FMCS 2016). Introducing state-listed species into natural habitats has legal considerations and logistical challenges that will lead to different constraints on site selections in each state. Constraints on reintroduction or augmentation sites often involve obtaining landowner consent and support, which takes time and resources, often incurred through community outreach programs. Even where restoration is on public land, public education and population monitoring programs are needed to ensure persistence once reintroduced (FMCS 2016).

Ecological context

Brook floater is a small freshwater mussel typically found in small and medium sized streams and rivers draining into the Atlantic Ocean, but they also inhabit large rivers such as the Potomac River and Delaware River, and occasionally lakes and ponds (Nova Scotia and Massachusetts) (USFWS 2018). Within these systems, brook floater reside in areas with low to moderate current, stable substrate composed of sand, gravel, and cobble, and relatively unimpaired water quality. Brook floater are considered host generalists, releasing their larvae in mucus strands to allow for passive entanglement by host fish (Wicklow et al. 2017).

While brook floater are still in nearly all states and provinces where they were historically found, their distribution has shrunk from 150 populations to 70-80 populations (USFWS 2018), with populations defined by occupancy within 12-digit Hydrologic Unit Code (HUC 12) watersheds. Declines have been attributed to dams, sewage and pollutant discharge, habitat destruction, habitat fragmentation, urban and agricultural land uses, riparian deforestation, and increased flooding and temperature caused in part by climate change (Wicklow et al. 2017). These same threats affect freshwater mussels globally (Haag and Williams 2014).

For the workshop, we focused the decision on restoration locations in Massachusetts and Connecticut, with the potential for broodstock from Maine, which has the healthiest populations of brook floater in the northeast U.S. region (Wicklow et al. 2017). In Massachusetts, brook floater are currently known to occur in five HUC 12 watersheds, which represents a decrease of 54% from eleven historically known populations (Figure 1). Of the remaining populations in Massachusetts, two appear to be relatively stable in the past 10 years, but longer-term declines are suggested from historic qualitative data. The other three populations in Massachusetts appear to be declining and may be relegated to only a small fraction of once occupied habitat. In Connecticut, brook floater populations are known to occur in eleven of twelve historically known HUC 12 watersheds, although only one of those eleven populations (Shepaug River) is considered viable (Figure 1, Wicklow et al. 2017). Intervention is needed to avoid the potential extirpation of this species from the majority of its historic state range. Planning appropriate restoration treatments requires additional data gathering and inter-watershed coordination.

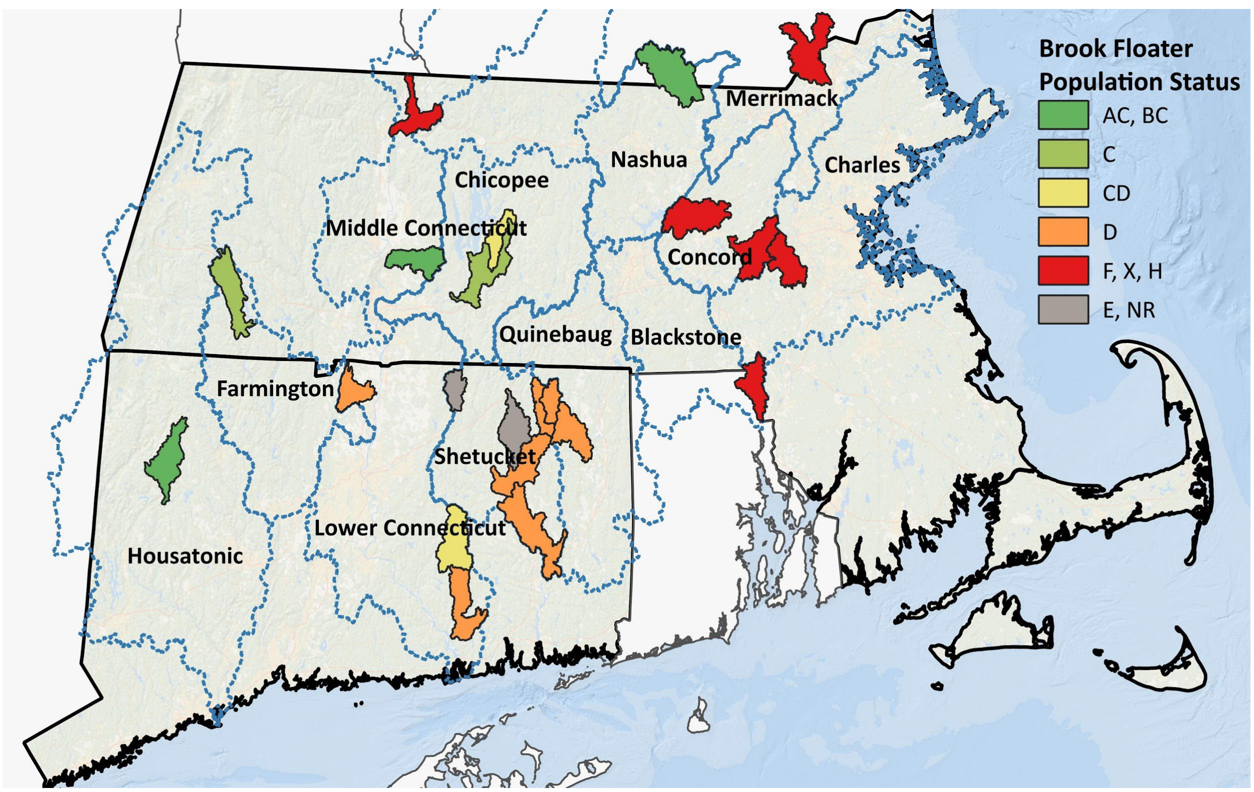

Figure 1. Map of historic and current populations of brook floater (*Alasmidonta varicosa*) in Massachusetts and Connecticut at the HUC 12 watershed scale. Blue dashed lines represent HUC 6 basins. Population status is based on element occurrence rankings available in NatureServe: AC, BC = excellent-fair, good-fair; C = fair ; CD = fair-poor ; D = poor ; F, X, H = failed to find in follow-up surveys and presumed extirpated, possibly extirpated; E, NR = verified extant, not ranked. Brook floater are not found in light gray areas of the states.

Surveys are needed in Connecticut since it has been over ten years since most brook floater survey work has been conducted and new monitoring protocols have been developed (Sterrett et al. 2018). In both states, uncertainties about population viability, genetic structure among watersheds, suitable unoccupied habitat, stressor abatement, and timescale of recovery made identifying an approach to population restoration of brook floaters difficult without a structured decision-making process.

Decision Structure

Objectives

We identified several means objectives to meet the fundamental objective of minimizing the probability of extinction of brook floater within the region (Massachusetts and Connecticut). Specifically, we had three ecological objectives that would reduce extirpation risk:

1. Maximize the number of populations (occupied HUC 12s) in the region
2. Maximize the number of occupied major basins (HUC 6s) in the region
3. Maximize the size of each population (# individuals within HUC 12)

These objectives aimed to increase redundancy within basins (#1) and representation across basins (#2) to provide safeguards from catastrophic disturbances, and to increase resiliency within populations via larger population sizes (#3) that maximize potential for population persistence and ability to use populations as broodstock for lab-propagated animals.

We also identified several objectives or constraints associated with risks to brook floater populations and costs:

4. Minimize disease risk to recipient populations
5. Minimize genetic diversity loss within populations
6. Minimize implementation and monitoring costs

While disease introduction is a major concern that could prohibit any actions, standard screening tests for mussel diseases are yet to be developed (Waller and Cope 2019). Thus, protocols focus on minimizing disease risk through procedures such as quarantine of broodstock (Gatenby et al. 1998) and depurating mussels before movement from captivity into the wild (Starliper 2009). Genetic diversity was a concern in terms of 1) local genetic diversity losses and associated population bottlenecks due to small populations and genetic swamping by introduced animals, 2) maintaining potential genetic differences across populations and basins for species adaptive capacity and 3) artificial selection based on the cohorts used (addressed by best practices). Costs to propagate mussels, reintroduce mussels, and monitor following restoration were additional considerations, but were considered standard based on the number of populations introduced.

Objectives were mapped to show relationships among means objectives and constraints and how they influence the fundamental objectives (Figure 2). Landscape and local scale factors, including connectivity along stream networks and watershed conditions (blue boxes; Figure 2), influence habitat quality, which in turn influences genetic diversity (Objective 5) and the production of brook floater. Genetic diversity and distance between brook floater populations affects resilience to stochastic events and this, along with disease risk (Objective 4), can also influence productivity. Productivity and survival of brook floater influence recruitment and the population size in an occupied HUC. The population size (Objective 3), number of occupied HUC 12s (Objective 1), and the number of occupied basins (Objective 2) all influence the probability of extinction within the region (green box; Figure 2), the fundamental objective. Implementation and monitoring costs were considered a constraint, but not mapped on the influence diagram (Figure 2).

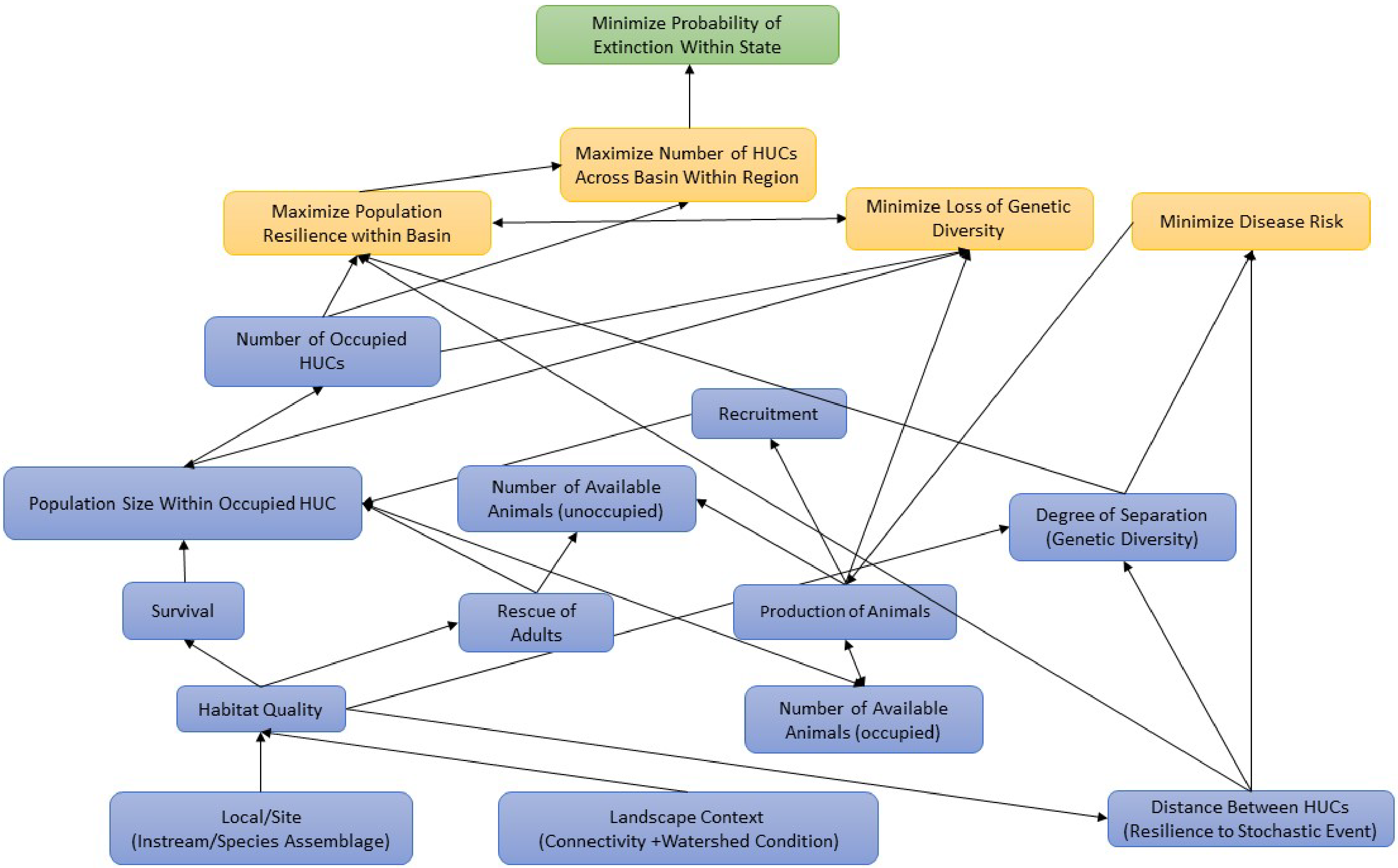

Figure 2. Influence diagram showing relationships among factors influencing habitat quality and production of brook floater (*Alasmidonta varicosa*) for addressing means objectives (yellow boxes) of maximizing number of occupied populations (HUC 12s) (Objective 1), number of occupied HUC 6 basins (Objective 2) and population size (Objective 3) toward ultimately minimizing probability of extinction within each state (fundamental objective, green box).

Alternative actions

Options for restoration were to augment existing populations with propagated mussels, reintroduce propagated mussels to watersheds where brook floater have been extirpated, or do nothing (Table 1). For the purposes of this workshop, we defined populations as occurring within HUC 12 such that a HUC is the geographical area considered to be occupied by a population. Augmentation was further separated based on the number of lab-propagated animals being added (i.e., restrained [fewer additions] or not); while we did not assign a specific number or proportion of animals as restrained, this action acknowledges the importance of not genetically overwhelming the population where introduced. In addition, we considered which populations would be sources of broodstock for propagation (i.e., donor sites) and whether the broodstock would be returned to the population from which they were taken (i.e., replacement vs no replacement). We considered population persistence, as approximated by current estimated population size, and habitat quality when deciding which options to consider. Not all options were considered for every population. For example, populations with high persistence could be a donor population for propagation but were not considered for augmentation. Habitat quality is also important for restoration; we do not want to place propagated animals where habitat is of poor or unknown quality. However, mussels from poor habitat may be considered as donor populations for broodstock (Table 1).

Table 1. Alternative actions considered for brook floater (*Alasmidonta varicosa*) based on population persistence (using population size, N, as a surrogate) and habitat quality. No action is an option for all combinations.

Persistence	Good Habitat	Poor Habitat
Vacant (0)	Introduce	Do nothing
Low (N<100)	Donor population for propagation (no replacement) Augment Restrained Augment	Donor population for propagation (no replacement)
Medium-Low (N=100-500)	Donor population for propagation (with replacement) Augment Restrained Augment	Donor population for propagation (with replacement)
Medium-High (N=500-1000)	Donor population for propagation (with replacement) Restrained Augment	Donor population for propagation (with replacement)
High (N>1000)	Donor population for propagation (no replacement)	Donor population for propagation (no replacement)

Predictive model

Within- and across-basin occupancy (Objectives 1–2), as well as population size (Objective 3), were predicted using elicited transition probabilities (Table 2). These transition probabilities were the result of two rounds of elicitation. Through discussion, participants produced a consensus transition probability for each habitat, current state, and action combination. Following the initial round of elicitation, participants evaluated the resulting table and adjustments were made to better reflect the consensus opinion on the relative transition probabilities across the set of starting conditions. The combined status across sites, accounting

Table 2. Probability of future population persistence/size for brook floater (*Alasmidonta varicosa*) (0: vacant; low: N<100; med-low: N=100–500; med-high: N=500–1000; high: N=>1000) for each action with current state/habitat combination. Transition probabilities were estimated based on collective/consensus expert opinion. Aug = augmentation of occupied locations; Prop = donor population for propagation; Replacement = broodstock returned to donor population

			Future Population Persistence				
Habitat	Current Population Persistence	Action	0	Low	Med-Low	Med-High	High
Good	0	Introduction	10	25	25	25	15
Good	0	No Action	100	0	0	0	0
Unknown	0	No Action	100	0	0	0	0
Good	Low	Augment	10	30	30	20	10
Good	Low	Restrained Augment	15	45	20	15	5
Good	Low	No Action	20	50	15	10	5
Good	Low	Prop - No Replacement	30	40	15	10	5
Unknown	Low	Prop - No Replacement	45	35	10	5	5
Unknown	Low	No Action	55	40	5	0	0
Good	Med-Low	No Action	15	15	45	20	5
Good	Med-Low	Prop w/Replacement	15	20	40	20	5
Good	Med-Low	Augment	5	15	30	30	20
Good	Med-Low	Restrained Augment	7.5	15	35	27.5	15
Good	Med-Low	Prop + Augment	10	15	40	25	10
Unknown	Med-Low	Prop w/Replacement	20	20	40	15	5
Unknown	Med-Low	No Action	20	30	45	5	0
Good	Med-High	Prop w/Replacement	5	10	30	45	10
Good	Med-High	Restrained Augment	5	5	15	45	30
Good	Med-High	No Action	5	10	30	45	10
Unknown	Med-High	Prop w/Replacement	5	10	40	40	5
Unknown	Med-High	No Action	5	20	40	30	5
Good	High	Prop - No Replacement	0	5	5	15	75
Good	High	No Action	0	0	0	10	90
Unknown	High	Prop - No Replacement	0	5	10	20	65

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for which sites were in each basin, provided the predicted results for Objectives 1–3. The within basin metric (Objective 1) was scored by totaling the number of occupied HUC 12 sites, and the across basin metric (Objective 3) was scored by totaling the number of HUC 6 basins with two or more occupied HUC 12 sites. The metric for population status objective (#3) came from a constructed scale score elicited from the participants. Through discussion and consensus, participants decided that on a 0 to 1 utility scale, a site with a population status of 0 resulted in 0 utility, a low population status had a utility of 0.2, a med-low status had a utility of 0.6, a med-high status had a utility of 0.9, and high status had a utility of 1. Summing these scores across sites produced the population status score.

Disease and genetic risks (Objectives 4–5) were combined and predicted based upon the distance between the donor and recipient sites, whereby donor populations from farther geographic distances have higher risk of disease and genetic differences from recipient sites than those from within the same HUC 6 basin. Elicited consensus risk scores were 0.25 for a recipient site in the same HUC 6 basin as the donor site, 0.5, for an adjacent basin, 0.75 for a non-adjacent a basin in the same region (watersheds of a major river), and 1.0 for a recipient site in another region. The risk scores were summed across sites to determine the total risk and assign the score to the distance to source metric in the decision analysis.

The cost objective (#6) was made up of two component costs, (1) the implementation cost of collecting, propagating, and adding individuals to a new site and (2) the monitoring cost of determining the population status of donor and recipient sites. Cost was measured with a unitless constructed scale representing the relative cost of one action in comparison to another. Participants determined that implementation cost depends on the current size of the donor population; low current size was assigned a cost score of 8, med-low of 4, med-high of 2, and high of 1, with the total implementation cost score equal to the sum of the costs for the utilized source populations. Monitoring cost was not dependent on population status, so the predicted monitoring cost score was equal to the total number of donor and recipient sites selected.

Decision Analysis

To assess solutions to the problem, we used a portfolio optimization approach, whereby all combinations of donor populations and restoration locations were considered, and the best solution (i.e., combination of donor and recipient sites with the highest utility) was identified. Potential restoration watersheds included currently occupied watersheds (four in Massachusetts, 11 in Connecticut) and selected vacant watersheds (five in Massachusetts, one in Connecticut) that may or may not have had historic brook floater populations. We considered two scenarios for harvesting broodstock. Scenario 1 included one site (Wesserunset Stream) in Maine, where the population is considered healthy and broodstock have previously been used for propagation in Massachusetts. Scenario 2 restricted sites to within Massachusetts and Connecticut. The portfolio optimization was conducted using integer programming (e.g., Guikema and Milke 1999) that iteratively selects which sites to use as donor and recipient sites and calculates the total utility (i.e., benefit) of each selection. The combination of donor and recipient sites with the greatest predicted utility is the optimal portfolio of sites to select. This optimization was implemented in Microsoft Excel using integer programming with solver as the optimization tool.

The utility of a trial set of donor and recipient sites was determined using multiple criteria decision analysis (Goodwin and Wright 2009). The analysis involves normalizing the predicted consequences for each objective to place them all on the same scale and then weighting the relative importance of each objective in comparison to the importance of the other objectives. The importance depends on the range of possible outcomes for each objective, and how important that range is relative to the range of outcomes for the other objectives. This weighting was elicited using a swing weighting exercise (Edwards 1971, Goodwin and Wright 2009). Participants indicated that obtaining a better result across the range of possible population size outcomes was most important, placing the most weight on this objective, and allocated the least weight to risk and cost objectives (Table 3).

Table 3. Weighting of selected objectives for brook floater (*Alasmidonta varicosa*) with associated metrics created by the seven stakeholders (represented as author's initials) at the workshop. Color coding ranges from highest (green) to lowest (red) weighting.

Objectives	1) # Occupied HUC-12s	2) # Basins with > 1 Occupied HUC-12s	3) Population Status	4/5) Distance to Donor Site	6a) Implement-ation Cost	6b) Monitoring Cost
Metric	sum # selected	count basins	persistence score	HUC/basin adjacency code	# donor sites * days based on pop status	# HUCs added to and removed from
Stakeholders						
DP	35	20	20	5	10	10
AR	35	10	50	3	1	1
AS	30	20	30	10	5	5
LS	30	5	30	20	5	10
JC	30	15	30	13	5	8
MK	30	15	40	10	2	3
PH	24	20	22	12	11	11
Average	**30**	**14**	**34**	**11**	**5**	**6**

While we only report the results from the most likely uncertainty outcome developed for this projection model, the transition probability elicitation allowed us to include three other uncertainty options in the projection model. These uncertainty options bound the range of uncertainty elicited from the panelists and can also provide uncertainty weighted (expected value) results. The predicted future status of a site can be determined by selecting any one of these uncertainty options for analysis: (1) most likely: the future state of a population is the state with the highest transition probability (the above results come from this scenario), (2) least desirable: the future state of a populations is the least desirable, i.e., least abundant, future state with a elicited transition probability greater than 0, (3) most desirable: the future state of a populations is the most desirable future state with a transition probability greater than 0, or (4) expected value: the utility of the future the transition probability weighted value across the set of possible future states.

The optimization model identified six HUC 12 watersheds for restoration: five in Massachusetts and one in Connecticut (Table 4). Selected restoration sites only included currently vacant watersheds, where restoration would involve novel introduction or reintroduction into the watershed, likely because these watersheds had the best potential for increasing population status. Results from Scenario 1 showed that Wesserunset Stream in Maine would be the best donor site for broodstock given its high population persistence (Table 4). If Maine was not considered an option for broodstock (Scenario 2), the headwaters of the Shepaug River (Housatonic watershed, Connecticut; Figure 1), Nissitissit River (Nashua watershed, Massachusetts; Figure 1), and Upper West Branch of the Farmington River (Massachusetts; Figure 1) were considered the best donor populations, as these were the sites with the next highest population persistence (Med-Low). The donor site for broodstock was within-basin for some sites (Connecticut Coastal) but not for other sites (Table 4).

Table 4. Sites (1=selected, 0=not selected) considered as recipient sites for restoration (introduction or augmentation) and donor sites for broodstock (by site number) for brook floater (*Alasmidonta varicosa*) based on optimized model run. Results of Scenario 1 (optimal; all 22 sites included; light blue) and Scenario 2 (Maine removed; gray) are included.

					Scenario 1	Optimal	Scenario 2	Maine Removed
#	**HUC 12 Name**	**HUC 6 Name**	**State**	**Current Population Persistence**	**Recipient**	**Donor**	**Recipient**	**Donor**
1	Stony Brook	Lower CT	CT	Low	0	0	0	0
2	Edson Brook	CT Coastal	CT	Low	0	0	0	0
3	Mashamoquet River	CT Coastal	CT	Low	0	0	0	0
4	Headwaters Shepaug River	CT Coastal	CT	Med-Low	0	0	0	0
5	Eightmile River	Lower CT	CT	Low	0	0	0	0
6	Nissitissit River	Merrimack	MA	Med-Low	0	0	0	0
7	Bachelor Brook	Lower CT	MA	Low	0	0	0	0
8	Jeremy River	Lower CT	CT	Low	0	0	0	0
9	Danforth Brook-Ware River	Lower CT	MA	Low	0	0	0	0
10	Upper W Branch Farmington River	Lower CT	MA	Med-Low	0	0	0	0
11	Beaver Brook-Shetucket River	CT Coastal	CT	Low	0	0	0	0
12	Sawmill Brook-Natchaug River	CT Coastal	CT	Low	0	0	0	0
13	Still River	CT Coastal	CT	Low	0	0	0	0
14	Bungee Brook	CT Coastal	CT	Low	0	0	0	0
15	Mount Hope River	CT Coastal	CT	Low	0	0	0	0
20	Winimusset Brook-Ware River	Lower CT	MA	0	1	47	1	10
28	Stillwater River	Merrimack	MA	0	1	47	1	10
38	Williams River	CT Coastal	MA	0	1	47	1	4
39	Sandy Brook	Lower CT	MA	0	1	47	1	6
45	Witch Brook-Squannacook River	Merrimack	MA	0	1	47	1	6
46	Hollenbeck River	CT Coastal	CT	0	1	47	1	4
47	Wesserunset Stream		ME	High				

Scenario 1 (with all sites included) resulted in higher populations status, higher distance to donor population, and lower implementation costs than Scenario 2 (Maine removed); however, number of occupied HUC 12s and number of basins with >1 occupied HUC 12 were the same with the two scenarios (Table 5). These results were based on the parameters established for the prototype; changes in metrics, metric weightings, and potential sites will all result in different outcomes. The range of possible outcomes based on uncertainty in the elicited transition probabilities shows that uncertainty has the biggest effect on Objectives 1, 2, and 3, with no effect on Objectives 4/5, 6a, and 6b (Table 5).

Table 5. Values for each metric for the optimized runs for Scenario 1 (all sites included) and Scenario 2 (Maine removed) for brook floater (*Alasmidonta varicosa*) restoration with the most likely uncertainty outcomes, the range of outcomes produced by the optimal actions from least to most desirable, and the expected value given uncertainty.

Objective	Scenario 1 Optimal	Scenario 2 Maine Removed	Range (least to most desirable) for Scenario 1	Expected Values for Scenario 1
1) # Occupied HUC 12s	14	14	1–22	22
2) # Basins with > 1 occupied HUC 12	3	3	0–3	3
3) Population status	4.8	4.8	0.9–18.8	8.2
4/5) Distance to donor site	5.5	2	5.5–5.5	5.5
6a) Implementation cost	6	24	6–6	6
6b) Monitoring cost	7	9	7–7	7

Uncertainty

Propagation and (re)introduction decisions are notoriously complex due to numerous, compounding uncertainties at various levels. To make the decision tractable and evaluate the various options, we made several assumptions about the level of uncertainty associated with each strategy. Discussion and evaluation of uncertainty sources allowed the group to identify future research and survey needs and protocols to reduce uncertainty in development of a final management decision. Where knowledge gaps were identified, the group collectively came to decisions or assumptions that would allow the continuation of the process based on our own experience with the animals and the literature. This approach to expert solicitation is not uncommon in data deficient processes (Smith et al. 2015; Fitzgerald et al. 2021). Here, we describe the important areas of uncertainty, our approaches to address and incorporate these uncertainties into our current decision framework, and future directions to address critical knowledge gaps.

Population status and viability

We recognized uncertainty in the data on population status of both donor (i.e., sources of broodstock) and recipient (i.e., locations for augmentation) populations of brook floater. First, very few assessments of population viability have been constructed for freshwater mussels, and viability likely varies by species. Further, quantitative population estimates are not available for many brook floater populations, so population size targets are not available for donor or recipient populations. To address this uncertainty, we modified abundance categories used in the Species Status Assessment for brook floater (USFWS 2018) to evaluate actions for a given population (Table 1). Then, we used expert elicitation from our panelists to estimate probability of future population state of donor and recipient populations (Table 2) and incorporated the range of responses to calculate the uncertainty around future state (Table 5). Our understanding of population status and viability could be further informed by continued surveys and research in these areas. Elicitation of expert opinion from the remainder of the BFWG and other experts could also better inform the level of uncertainty around population abundance.

Broodstock collection and stocking density

Uncertainty exists in the mussel stocking density (total number) needed at recipient populations to effectively increase the probability of positive change in the future status of an augmented or introduced population. We directly acknowledged effects of stocking density on population status and risk to populations by including restrained (i.e., limited number stocked) and unrestrained augmentation as separate actions, but uncertainty on appropriate stocking densities remains. There is also uncertainty around the number of gravid females needed to produce this stocking density through captive rearing. For this analysis, we made assumptions of the number of female broodstock needed from donor sites and the number of juveniles needed to change the future state of a recipient population. We did not assign a specific number to either of these, but assumed a single unit of broodstock (e.g., 10 females) could produce 1000 juveniles of adequate genetic variation to stock at a recipient site and increase the recipient population to a targeted high population status. While guidance suggests that a minimum of 50 gravid females is needed to capture the genetic diversity (Patterson et al. 2018), that number is not feasible for brook floater. We also assumed that female broodstock could be returned to their donor populations with limited effect on donor population survival, given appropriate protocols are developed to minimize disease risk transfer. Both of these assumptions are not without risk, and would require a future stock management plan, nevertheless we used these estimates to follow recommendations of McMurray and Roe (2019) to minimize harm to donor and recipient populations. As with population status and viability, we incorporated the uncertainty of future population status of donor and recipient sites through expert elicitation (Table 2). Further information from pilot introductions and monitoring of recipient and donor populations will provide more informative estimates of broodstock needs and juvenile stocking targets. Additionally, further expert opinion from established restoration programs would also provide more informative data.

Habitat condition

Uncertainty exists surrounding the ability of habitat to support brook floater populations at sites that are currently unoccupied. As such, managers are cautious to attempt reintroductions in habitats where there are currently no brook floater or other mussels. However, the absence of mussels may reflect previous habitat alterations that have subsequently been remedied. We used the brook floater habitat suitability model (Sean Sterrett, Monmouth University, BFWG meeting 27 September 2019) and our own expertise (JC, PH, LS, AS) to identify unoccupied HUC 12 watersheds for reintroduction. We recognize that habitat may still not be suitable at all streams or reaches within a watershed, and that ground truthing of our approach would be necessary to identify potentially suitable habitat. Sites could be selected that exhibit similar habitat characteristics to those occupied by brook floater, as determined by a habitat assessment approach from the Brook Floater Rapid Assessment guidelines (Sterrett et al. 2018). We did not quantify or evaluate uncertainty in habitat condition within our decision model but addressed uncertainty of habitat suitability at recipient sites through deferred evaluation of habitat at potential sites. Further evaluation of habitat needs for brook floater and assessment of unoccupied watersheds is needed to inform potential watersheds to include in future iterations of the optimization model.

Management units based on genetics

Little is known about the genetic structure of brook floater throughout the range, and genetic structure among populations within a geographical area. Such data are not always available prior to a decision toward population restoration. Given these knowledge gaps, we used the assumption that populations within a HUC 12 watershed could be defined as a single management unit as demes within this geographical unit were likely more genetically similar than to neighboring basins (McMurray and Roe 2019). We further assumed that neighboring HUC 12s within the same HUC 6 basin would be the next closest in genetic diversity, and populations within an adjacent HUC 6 would be the next best source for genetic material, assuming the watersheds were ecologically similar (Patterson et al. 2018). These assumptions informed our distance to donor site metric values. We did not quantify uncertainty in genetic management across management units but used the assumptions above to donor populations by the next closest basin. Range-wide genetic analysis and local to regional scale comparisons of population genetic structure are needed for brook floater to reduce uncertainty in developing stock management plans for restored populations. In the absence of these data, as in this analysis, managers are left with geographic distance between watersheds as a proxy for genetic distance.

Mussel diseases

Concern is growing for freshwater mussel health as new pathogens have been identified, which may be linked to die-offs of some populations (Richard et al. 2020). There are still substantial unknowns around mussel pathogens and possible transmission through propagation and reintroductions, and thus we made several assumptions regarding disease management in the absence of information on pathogen existence in donor or recipient sites. First, we assumed that following our approach for reducing genetic risks by prioritizing the nearest neighboring donor population would also reduce the likelihood of transmission of novel pathogens to the recipient population. We also assumed that protocols and standard operating procedures (e.g., decontamination of all collection equipment, quarantine of broodstock within propagation facilities, quarantine and pathogen screening of juveniles prior to stocking at recipient site) would be employed to reduce the risk of pathogen introduction following recommendations by Simmons et al. (2018) and McMurray and Rowe (2019). Again, we did not quantify uncertainty, but relied on these assumptions to allow us to develop a decision framework. Better understanding is needed of background pathogen presence in freshwater mussel populations and how to minimize transfer from one population to another.

Implementation and Monitoring Costs

Without identified propagation and monitoring costs for brook floater, it is difficult for managers to evaluate the scale of a restoration effort. Implementation (including propagation) and monitoring costs were considered secondary to the population objectives based on the results of our importance weighting (Table 3). We assumed that the cost for implementation would be standardized depending on the number of reintroduction units needed, and that monitoring costs would be standardized by the number of restoration sites. We did not evaluate alternatives to the number of recipient sites or stocking density in terms of the implementation costs and assume one unit of implementation cost per propagation donor site and one unit of monitoring cost per restoration site in our evaluation of alternatives. The importance of costs were integrated into our swing-weighted objectives through expert elicitation; the mean weighted score was used as the evaluation metric for costs and we did not evaluate uncertainty around this score. More precise cost estimates could be determined through evaluation of similar restoration programs and incorporated into the optimization model directly. Uncertainty in costs would be more important when expanding our optimization model to multiple reintroduction efforts to evaluate alternatives of single or multiple reintroductions.

Discussion

Value of decision structuring

There was consensus among workshop participants that decision structuring was a valuable tool for unpacking complex problems associated with population restoration. An important component of the process was recognizing region-specific differences when considering alternative actions and defining language. While the problem was focused in the northeast U.S., participation by a state manager from South Carolina (MK) ensured that issues relevant to other regions were considered. Regulatory differences between states may ultimately govern final decisions regardless of the overall objective based on what is allowed in their management area and the interests of others (e.g. higher authority, public opinion). Understanding the restrictions that each state manager was working within strengthened the ability to cooperate in the future outside of the workshop. Furthermore, language defined in the decision structuring process (e.g. augmentation vs reintroduction, watershed vs. basin) created a common ground of understanding that can be adopted by the BFWG and other managers tackling similar problems.

Decision structuring created a space outside of public scrutiny to explore any negative trade-offs linked to a decision. When managers are responsible for advocating for a conservation action, it can be difficult to consider all outcomes; transparently acknowledging any negative aspects could be used against the agency or the individual at a later point. State agency representatives agreed that being removed from the advocacy role to participate in the decision process allowed them to explore negative consequences of actions, exposed their personal values (e.g. weighting objectives) and was essential in reaching the fundamental objective. All participants agreed that the ability to define these objectives despite numerous uncertainties is a powerful result of the process.

Further development

The process of model development was a valuable exercise that yielded informative outputs and insights. With additional investment of time and energy beyond the 5-day, 36-hr workshop, the current model could be refined and expanded in many ways. For example, additional alternative actions (e.g., the number of stocking sites and stocking densities; translocation) could be examined, additional expert elicitation (e.g., fish health experts on our approach to valuation of disease risk) could be sought, and cost estimates could be included as part of the optimization. Model results highlighted a potential constraint that should be considered: loss of donor population resilience that could result from using a single donor stock (the optimal finding of the current model). As new information becomes available in the next 1–3 years from genetic, population, and habitat assessments, the model could also be improved. Finally, sensitivity analysis could help managers better understand trade-offs. The degree to which model outputs would be improved because of new information and reduced uncertainty remains unknown but it seems likely that ground-truthing of results and subsequent field assessment of habitat suitability for stocking will always be necessary.

Prototyping process

The rapid prototyping process was challenging to complete because of the unknown risks (e.g. genetic swamping) that were associated with the alternative actions. Omitting detail (e.g., population status, habitat suitability) when first drafting objectives crippled the ability to move forward and ultimately resulted in a collective decision to revisit the means objectives for the purpose of adding detail. The means objectives were expanded to include risk; a trade-off between increasing population size and the uncertainty associated with the alternative action. By including categories in the level of population persistence (low, med-low, med-high, high), decision makers could then assign their own population numbers to the categories that represented occurrence in their state (e.g. the transition from med-high to high was set at 1,000 here, but could be redefined), although for the purposes of the workshop, the group used the same numbers in persistence categories regardless of state jurisdiction. The process allowed experts to weigh objectives without considering the ultimate consequences; this was extremely valuable in incorporating personal values into the decision process without being paralyzed by the risks associated with the alternative action. The weights individuals placed on the objectives filtered out the alternative actions and revealed each experts' personal values.

One collective insight on the process was the importance of defining or avoiding ambiguous terminology like "viable" that was linked to unknown information, thus using specific language was imperative to mutual understanding. Other important insights included the importance of being spatially explicit in defining population resiliency, defining the overall scope by selecting which states to include in the case study, and defining the HUC size to focus conservation actions on.

The risks associated with alternative actions helped the group identify future work that could reduce uncertainty. The uncertainty around genetic differences across populations encouraged federal partners to begin opportunistic sampling for range-wide assessment on population genetics. At the completion of the workshop, state agency participants emphasized the appreciation for having means objectives and a fundamental objective that they could apply in their state. Overall, participants agreed the process was extremely valuable and that it was carried out in a way that could be applied to partners throughout the BFWG.

Conclusions

The structured decision-making workshop aimed to develop a process for making decisions about locations for restoration actions, including sources of broodstock and locations for reintroduction or augmentation, which can be applied to different regions throughout the range of brook floater. As discussed, the workshop was essential for developing a common language needed to define objectives and identify alternative actions, as well as to identify uncertainties and approaches to making decisions considering uncertainties. After sharing results of the workshop with state managers and experts working with brook floater throughout the range during a BFWG monthly meeting, it became easier for states to identify what information they needed to pursue propagation and restoration. While some states did not need this process to identify locations for restoration (i.e., recipient locations were obvious or restoration is not being considered), others found it helpful to move forward with population and habitat assessments with the goal of re-introduction or population augmentation in the future (BFWG meeting notes; 28 Feb 2020). Specifically, several states may be using the new range-wide species distribution model (Sean Sterrett, Monmouth University, BFWG meeting 27 September 2019) to prioritize watersheds for population and habitat assessment and in-situ tests of growth and survival of propagated mussels. The optimization model is flexible to be adapted at different spatial scales and to include different potential donor and recipient watersheds, making it useful as new information is collected.

While reintroduction or augmentation of lab-propagated mussels is likely an important component of mussel restoration plans, especially where populations are at critical low levels (FMCS 2016), this conservation approach is not without concerns. Importantly, it is essential that restoration activities do not harm existing mussel populations through disease transmission, genetic swamping, or loss of individuals in donor populations (Strayer et al. 2019). Moreover, propagation and reintroduction is time-consuming and expensive, so it is critical to ensure that propagated mussels are released in locations to maximize their success (Strayer et al. 2019). The USFWS has developed a propagation policy for freshwater mussels that can help guide conservation plans (USFWS 2000), which are critical to develop before any restoration takes place.

State managers are making conservation decisions based on multiple species, including other freshwater mussel SGCN species, and in the context of other management actions (e.g., land protection) that protect habitat for multiple terrestrial and aquatic species. As such, population restoration is only one part of larger conservation decisions. Despite this, an evaluation and process for making decisions related to one conservation action (population restoration of propagated mussels) is critical for population restoration to be considered an option in a larger conservation approach. Given the high complexity of such decisions, structured decision making will continue to be a useful tool to address uncertainties and frame an approach to making critical conservation decisions.

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