Natural Resource Damage Assessment and Restoration Best Practices: Freshwater Mussels (2023)

U.S. Department of the Interior

Office of Restoration and Damage Assessment

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EXECUTIVE SUMMARY

Freshwater mussels, which are currently among the most rapidly declining fauna in the world, are located in many Natural Resource Damage Assessment and Restoration (NRDAR) case sites. This document has been prepared in cooperation with Federal, Indigenous, and State malacologists (mollusk scientists), environmental toxicologists, restoration specialists, and other subject matter experts to provide best practices for freshwater mussel injury determination, early identification of restoration opportunities, injury quantification and damages determination (also referred to as claim development), and restoration planning, implementation, and monitoring. The experts address the effects of hazardous substance releases and oil spills on freshwater mussels' complex life histories and essential ecological roles, and offer solutions that will lead to the restoration, recovery, and protection of these organisms that provide important ecosystem services.

This document is organized around the phases of an NRDAR case (initiation, assessment and restoration). Practitioners will find:

- A mussel case development flow chart (Figure 1)
- An injury assessment decision tree (Figure 2)
- Details on relevant types of toxicity tests and measured endpoints with suggestions for translation results to mussel loss (injury) (Table 1)
- A description of the functional attributes of mussel habitat
- Early consideration of restoration types and relevant injury quantification approaches (Table 2)
- Decision points for restoration scaling
- A matrix connecting damages determination methods with available restoration types (Table 3)
- A checklist of mussel and host restoration cost categories for use in cost estimation for damages determination (Table 4)
- Ideas for developing restoration objectives, metrics, and performance criteria
- Information on the use of restoration/recovery tracking wheels (Figure 3) and tracking factors for performance measures in restoration planning (Figure 4)
- Considerations for successful restoration planning
- Current best practices for mussel restoration implementation
- General monitoring of ecological restoration at contaminated sites (Figure 5)
- Universal monitoring metrics for freshwater mussel or host restoration projects (Table 5)
- A substantial set of curated references plus supplementary information on economic methods, propagation facilities in North America, and mussel ecosystem services, among other topics

Subject matter experts developed much of the content in this document through participation on several of the Department's earliest NRDAR cases. Mussel production facilities have, and continue to make great strides in filling the data gaps in the life histories of many species, including those facilities that were established from settlement proceeds from the Certus NRDAR case in the Clinch River. After 20+ years of restoration with Certus and other mussel cases, restoration cost estimation has become more robust, and advancements in mussel toxicology are steadily being made by the scientific support from the U.S. Geological Survey. The best practices described in this document will continue to evolve as our knowledge progresses. As such, this is intended to be a living document with expectations to periodically update it as new information is made available.

LIST OF ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
AVS	Acid-volatile sulfide
BIA	Bureau of Indian Affairs (DOI)
BMP/BP	Best Management Practice/Best Practices
CERC	Columbia Environmental Research Center (USGS facility)
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (Superfund)
CET	Cost Estimation Tool (FWS)
CFR	Code of Federal Regulations
CPUE	Catch per Unit Effort
DARTS	Damage Assessment and Restoration Tracking System (ORDA)
DMY	Discounted Mussel-Year
DOC	Dissolved organic carbon
DOI	United States Department of the Interior
EC	Effects concentration
HaBREM	Habitat-Based Resource Equivalency Method (aka Biomass REA)
HEA	Habitat Equivalency Analysis
LC	Lethal concentration
LOEC	Lowest observed effects concentration
mm/m	Millimeters/meters
NGO	Non-Governmental Organization
NOEC	No observed effects concentration
NPL	National Priorities List (ref: CERCLA)
NPS	National Park Service (DOI)
NRDAR	Natural Resource Damage Assessment and Restoration
OPA	Oil Pollution Act
ORDA	Office of Restoration and Damage Assessment (DOI)
PRP/RP	Potentially Responsible Party/Responsible Party
RCRA	Resource Conservation and Recovery Act
REA	Resource Equivalency Analysis
RIM	**R**estoration Planning and **I**mplementation, and **M**onitoring Oversight
RSU	Restoration Support Unit (ORDA)
SL	Shell length
SME	Subject Matter Expert
SOL	Office of the Solicitor (DOI)
TOC	Total organic carbon
TSS	Total Suspended Solids
USEPA (EPA)	United States Environmental Protection Agency
USFWS (FWS)	United States Fish and Wildlife Service (DOI)
USGS	United States Geological Survey (DOI)

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Many thanks to all of those involved in this project. Without their dedication and commitment, this effort would not have been possible.

Introduction

This document is designed to assist Natural Resource Damage Assessment and Restoration (NRDAR) practitioners in navigating the native freshwater mussel (order Unionida[1]) injury determination, quantification and restoration process under Federal law such as the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and the Oil Pollution Act (OPA). A synthesis of relevant information about mussels is provided. This collaborative effort, funded by the Department of the Interior's (DOI; Department) Office of Restoration and Damage Assessment (ORDA), brings together Federal, Indigenous, State, non-governmental organizations, and academic partners who have knowledge and experience with mussels and/or developing natural resource damage claims for mussels. The resulting best practices (BPs) are intended to be used by NRDAR practitioners who have expertise with contaminants and an intermediate level of knowledge of NRDAR case development. The structure of this document follows the general framework of a NRDAR case (Figure 1), including injury determination, early identification of restoration opportunities, injury quantification and damages determination (also referred to as claim development), and restoration planning, implementation, and monitoring.

Three NRDAR case categories are addressed throughout:

1. Event (release of hazardous substance or oil spill; can include physical injury under OPA);
2. Long-term, chronic exposure sites (also called "legacy" sites, e.g., CERCLA National Priorities List (NPL) sites, Resource Conservation and Recovery Act (RCRA) sites); and
3. Remedial actions (e.g., environmental dredging, hardscaping performed under CERCLA; not applicable to RCRA actions).

The Resources section provides a curated set of references expected to be useful in NRDAR cases that include freshwater mussels. To help contain the length of the primary text, supporting appendices are provided with supplementary information.

This document is intended to remain current as a living document. ORDA intends to periodically update the BPs and this document as freshwater mussel NRDAR practice develops.

[1]See Williams et al. (2017) for a revised classification and list of the freshwater mussels of the United States (U.S.).

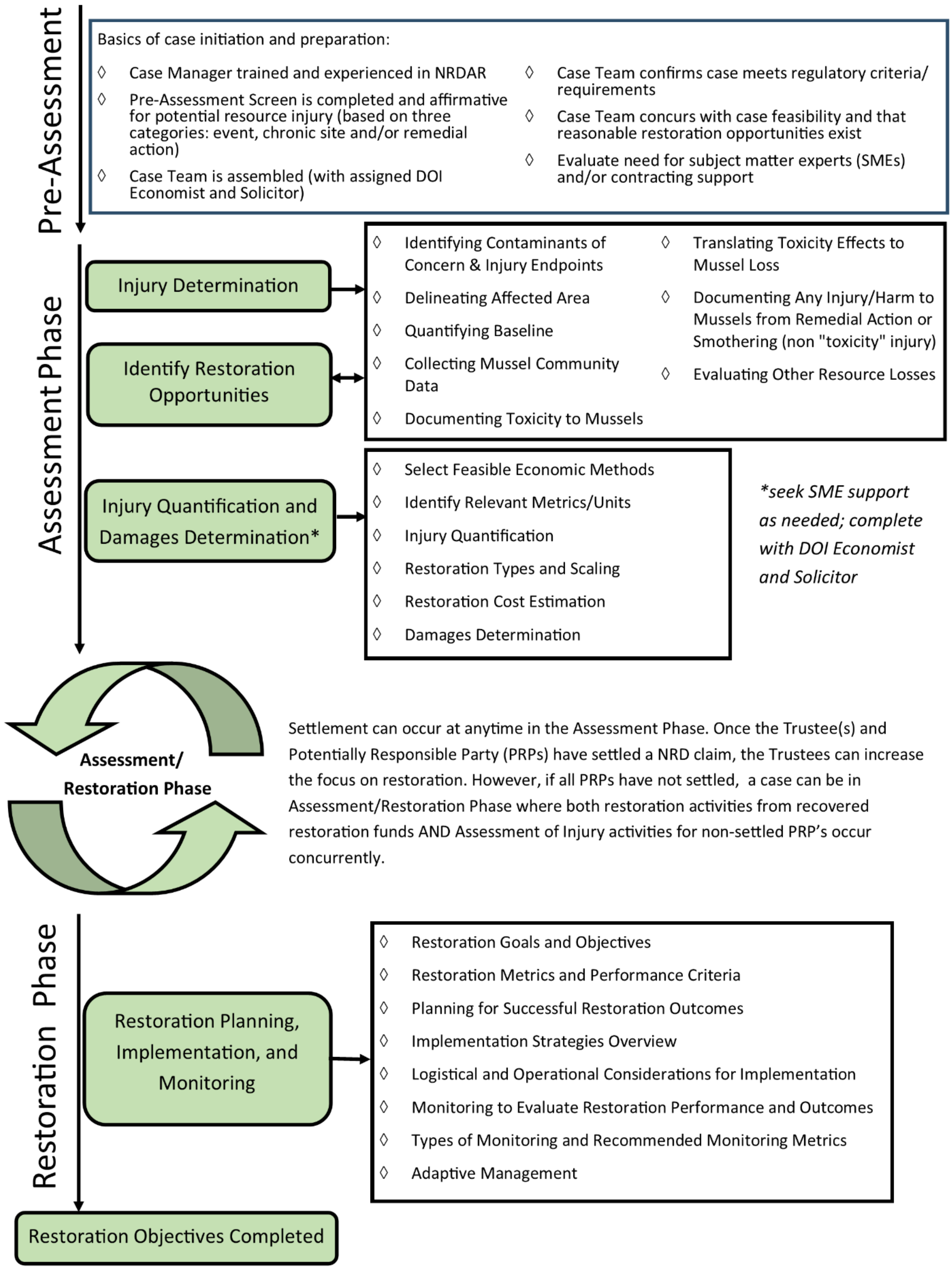

Figure 1. NRDAR Case Development Framework

ASSESSMENT: Injury Determination

For NRDAR cases involving potential injury to mussels, the ecological assessment can focus on quantifying losses to mussels (e.g., through use of mussel surveys), or a loss or decrease of services from mussel habitat as a result of exposure to contamination. The Mussel Injury Assessment Decision Tree is a tool for NRDAR practitioners to identify data needed to begin the assessment process (Figure 2). This information would be in addition to any standard data collection on the contaminant or remedial action impacts (e.g., source, concentration). Key considerations for each of the three NRDAR case categories include:

1. Event (release of hazardous substance or oil spill)
   - Availability of pre-event mussel community data (baseline)[2]
   - Selection of appropriate reference site(s) (if pre-event data are not available)
   - Collection of event-related mortality data[3]
   - Collection of post-event mussel community data[4]
   - Availability/collection of abiotic data
   - Spatial extent of the area of contamination[5] and mussels ("affected area"[6])
   - Availability of published toxicity threshold data/criteria[7]
   - Conduct toxicity tests, lethality endpoint (if appropriate)
   - Collection of sublethal toxicity test endpoint data (growth and reproduction, if appropriate and can translate to mussel loss)
   - Effect of time (e.g., duration of injury, natural recovery, changes in baseline)

2. Long-term, chronic exposures (e.g., NPL sites, RCRA sites)
   - Availability of historical mussel community data
   - Availability/collection of contemporary mussel community data
   - Selection of appropriate reference site(s) with similar watershed characteristics
   - Availability/collection of abiotic data
   - Spatial extent of the area of contamination and mussels ("affected area")
   - Availability of published toxicity effects data
   - Conduct toxicity tests, lethality endpoint (if appropriate)
   - Collection of sublethal endpoint data (if appropriate and can translate to mussel loss; see below)
   - If optimal habitat within the contaminated area is unoccupied, collect appropriate data to determine if toxicity has extirpated this population and prevented recolonization

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[2] Consult with state and federal malacologists on availability of baseline data.
[3] Observed mortality is a visual mussel kill. The Trustees can contact subject matter experts (SMEs) to support documentation for purposes of NRDAR. Lethal events should consider specimen identification and tissue preservation of any mortalities, and chain of custody be maintained through case completion. Collecting permits are required for pursuing, surveying, sampling, capturing, or handling any state or federally protected species.
[4] Depending on released substance, consider whether site cleanup is needed before post-event surveys can be initiated. Data collected should be similar to baseline and/or event-related mortality to facilitate quantification and comparison.
[5] Document contamination (spatially and temporally) and extent that contaminant exposure is likely to occur.
[6] Criteria for mussel habitat include depth, flow, substrate characteristics (sand, gravel, cobble, etc.), and pebble counts. Suggest contacting SMEs to assist Trustees with documentation to support the NRDAR.
[7] Toxicity thresholds relate to water and/or sediment concentrations that may need to be collected and analyzed.

- Effect of time (e.g., duration of injury, natural recovery, changes in baseline)

3. Remedial injury (e.g., dredging under CERCLA; not applicable to RCRA actions)
   - Collection of pre-remediation mussel community data
   - Collection of post-remediation mussel community data (if appropriate)
   - Spatial extent of the remediated area
   - Post-remediation changes in habitat conditions
   - Effect of time (e.g., duration of injury, natural recovery, changes in baseline)

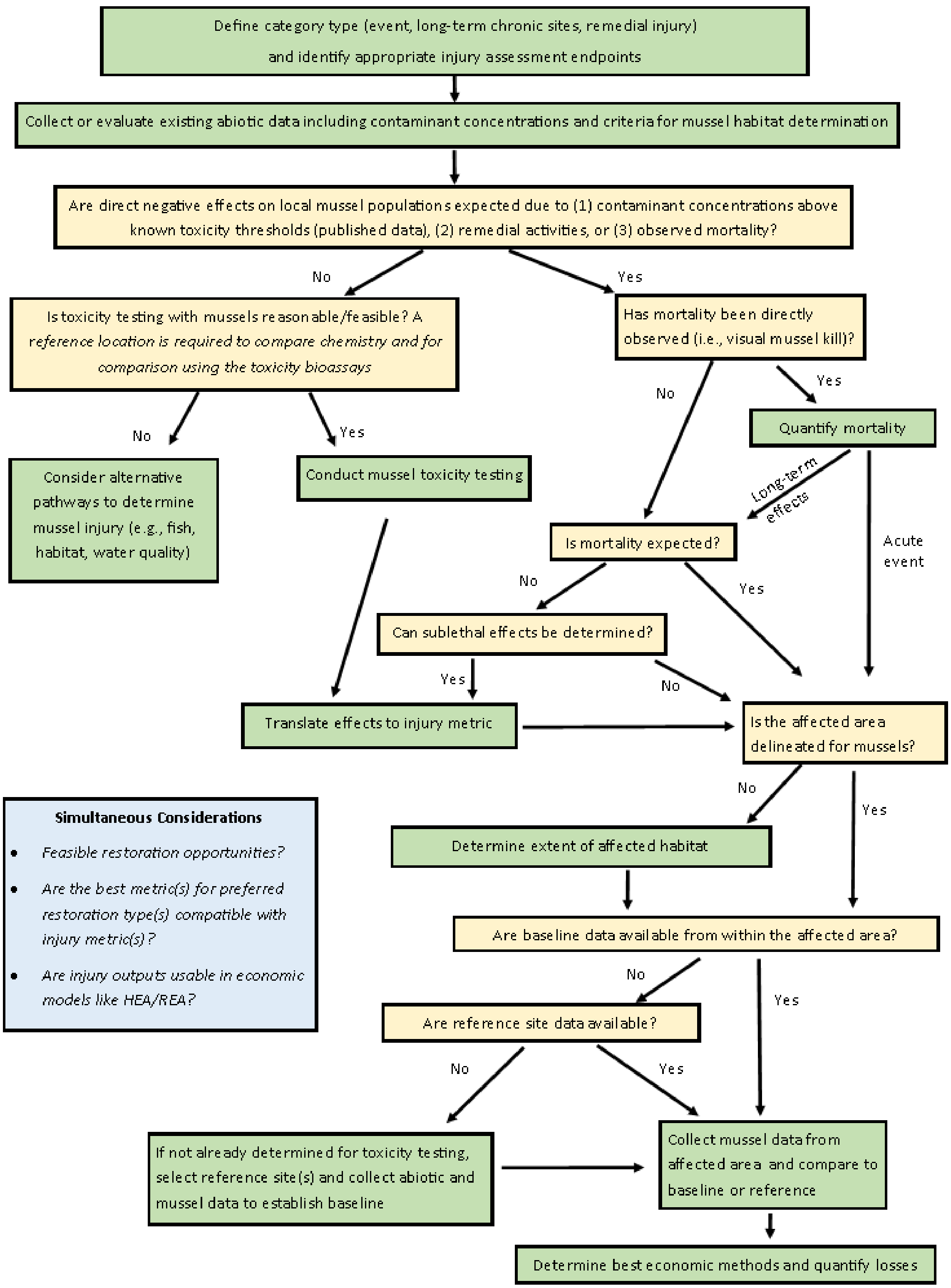


Figure 2. Mussel Injury Assessment Decision Tree

Injury Endpoints and Effects Levels

For events that cause a visually observed mussel kill, the initial focus should be on collecting ephemeral abiotic data and quantifying mortality with appropriate sample preservation and documentation, and then potential long-term or chronic effects can be determined as follows. For other contaminant-related injury assessments, case managers should develop a thorough understanding of the contaminants present, their environmental behavior (including the environmental variables that ameliorate or enhance toxicity), and mechanisms of action leading to potential toxicological effects on mussels. Development of a conceptual model is recommended to illustrate contaminant movement within the environment and potential pathways of mussel exposure and resulting toxicity. A conceptual model also facilitates development, review, discussion, and refinement of assessment objectives.

Once preliminary abiotic data have been collected and evaluated, the expected environmental behavior of the spill- or site-related contaminants should be ascertained. Environmental behavior is affected by contaminant properties such as water solubility and hydrophobicity, the primary source of contamination (e.g., runoff, groundwater transport, direct discharge, legacy impacts to sediment), the presence of other contaminants, as well as properties of the water body, including surface water quality (e.g., temperature, flow, pH, hardness, dissolved organic carbon (DOC) concentrations), and sediment properties (e.g., grain size, total organic carbon content (TOC), acid-volatile sulfide (AVS) content). Expected environmental behavior of the contaminants of interest can inform collection of additional abiotic data and ultimately, relevant routes of mussel exposure, which are life-stage specific (Cope et al. 2008). See Cope et al. (2008) for an evaluation of the pathways of exposure to contaminants for all four life stages (free glochidia, encysted glochidia, juveniles, adults) of mussels.

The potential routes of mussel exposure include:

- Surface water—Glochidia (free), juveniles, adults, and their gametes
- Sediment —Juveniles and adults
- Porewater—Juveniles and adults
- Hosts—Glochidia (encysted)
- Diet—Juveniles (pedal and filter feeding) and adults (filter feeding)

Once potential pathways of mussel exposure are understood, a screening-level analysis can be conducted to determine potential for effects on freshwater mussels. The utility of a screening-level analysis depends on the information available, and in many cases, it will not provide enough information to quantify an injury. However, it can be useful for determining preliminary thresholds, assessing likelihood of an injury, and focusing additional data collection.

Concentrations of contaminants can be evaluated relative to screening criteria, including:

- National water quality criteria and state water quality standards (datasets behind these documents will often be a summary of aquatic toxicity information in which the relative sensitivity of mussels and other mollusks can be ascertained)
- Sediment quality guidelines
- Known toxicity thresholds for mussels
    - Literature search
    - Database of literature for freshwater mussel toxicity (last updated 2016)
    - Ecotox (https://cfpub.epa.gov/ecotox/)
    - Comparison to reference or background
- Known toxicity thresholds for other mollusks as surrogates for mussels
- Known toxicity thresholds for fishes

- Literature search
- Ecotox (https://cfpub.epa.gov/ecotox/)

For some contaminants, toxicity to mussels is well documented. Examples include, but are not limited to ammonia, some metals (e.g., aluminum, copper, nickel, and zinc), and major ions (e.g., chloride and potassium) (Wang et al. 2007ab, 2010, 2017, 2018abc, 2020ab). In these cases, a screening-level analysis, combined with field assessments of the mussel community (discussed more below), may be sufficient for injury determination. In other cases, the potential toxicological effects of contaminants on freshwater mussels may need to be established with toxicity testing. Before proceeding with toxicity testing, an expected mechanism of toxicological action should be determined for contaminant(s). Mechanisms of action and resulting toxicological effects differ greatly between groups of aquatic organisms, broad classes of contaminants (e.g., inorganic vs. organic), as well as specific contaminants within these broad classes (e.g., ammonia vs. nickel) (Randall and Tsui 2002, Brix et al. 2017, Wang et. al. 2017). Once a mechanism of action is identified, selection of appropriate toxicity tests, environmental media, and test endpoints should be guided by potential pathways of exposure and affected lifestage(s).

Laboratory toxicity testing with freshwater mussels may consist of testing effects of contaminants in water only, sediment only, or in some cases, water + sediment, with acute or chronic durations and associated endpoints (generally mortality or immobilization in acute studies, as well as growth and/or biomass in chronic studies). Standard methods for laboratory toxicity testing with freshwater mussels have been developed for water-only exposures of glochidia and juveniles (ASTM 2020a). Exposures of glochidia are water-only and acute, and such methods are less complex than other tests. However, their applicability to injury assessments may be limited to cases where contaminant concentrations cause nearly 100% mortality (Table 1 and see below). Juvenile mussels are commonly used in toxicity tests as a result of their responsiveness to multiple exposure pathways and generally greater sensitivity compared to adults (Cope et al. 2008). Juveniles can be tested in acute (water-only) or chronic tests (water or sediment); for chronic tests the most used endpoints are growth and biomass (Table 1). Guidance for testing sediment toxicity with freshwater mussels is provided in a broader standard test methods document for freshwater invertebrates (ASTM 2020b). Although adults are not commonly used for freshwater mussel toxicity testing, the potential for measuring endpoints related to reproduction and energy storage, and developing linkages between energy storage and reproductive potential, has broad implications for freshwater mussel injury assessments and warrants consideration to supplement commonly implemented tests (Ciparis et al 2019).

Most freshwater mussel species have never been utilized in toxicity testing and many such species may not be suitable for testing due to an inability to produce large numbers in culture. With a vast majority of mussels untested, the use of standard surrogate species is commonplace, saving resources and time while fostering confidence in the relevancy of data obtained from surrogate-derived toxicity testing relative to the taxon of interest. Wang et al. (2017) demonstrated that commonly tested species of mussels perform well as surrogates for untested mussels. The work included testing a wide phylogenetic range of mussels to a variety of chemicals. Pollutant sensitivity of *Lampsilis siliquoidea,* the most commonly tested mussel species, is within a factor of 2 relative to other mussels 73% of the time and always within a factor of 5 (Raimondo et al. 2016). This type of information is exceedingly practical to determine the adequacy, and associated uncertainties, of using surrogate species.

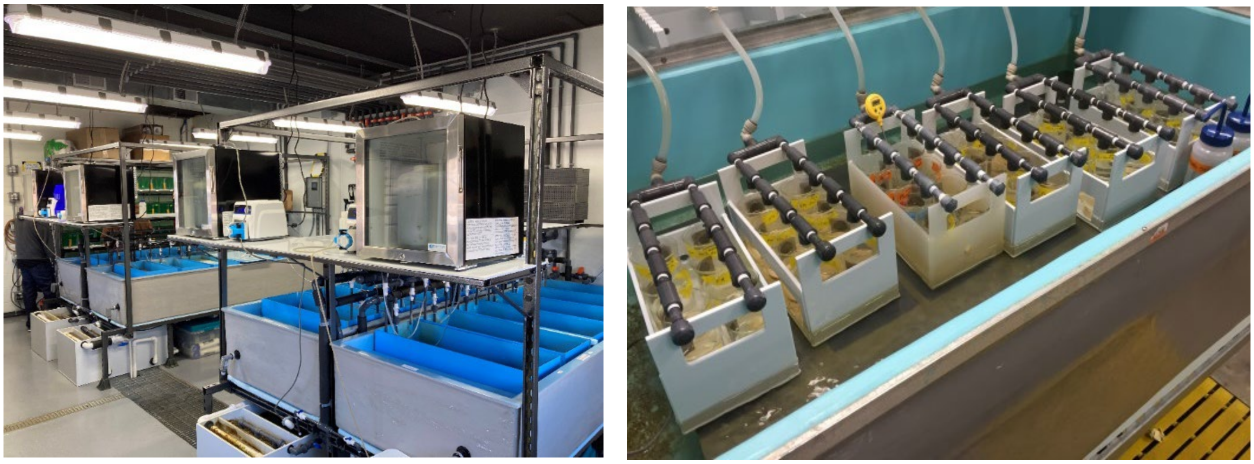
For some cases, mixtures of contaminants may be present in water and/or sediment. If these mixtures can be collected for testing in a laboratory setting, or replicated in a laboratory setting, laboratory toxicity testing may be appropriate. However, in some cases, the environmental conditions are too complex to replicate in laboratory toxicity tests. *In-situ* toxicity testing may be appropriate in these cases. *In-situ* tests may be acute or chronic and can utilize juvenile or adult mussels. However, to be effective in injury assessment, careful consideration must be given to selection of reference and impacted sites, exposure conditions, and presence of confounding environmental factors (e.g., sedimentation) that could cause mortality or growth/biomass effects unrelated to the presence of contaminants.

Toxicity testing results are typically reported as concentrations that are lethal (LC) or cause effects (EC) to a certain percentage of the test population (i.e., LC_{50} is the lethal concentration for 50% of the population). There are different types of effects which need to be specified when considering EC values (for example a concentration associated with a test population's 20% reduction in growth over the course of the test would be one EC_{20}). Thresholds for no observed (NO) or lowest observed (LO) effects may also be developed. These results need to be converted to loss of mussels for injury quantification. Table 1 presents a preliminary guide for translation of toxicity testing results into loss of mussels. Briefly, measured environmental contaminant concentrations (x) can be compared to LC/EC percentages and the percentages converted into loss for the mussel population. Results of acute tests are the easiest to translate, as LC_{50} = a 50% loss of individuals in the population, which can be further translated to the mussel community. For glochidia, only concentrations $\geq LC_{100}$ are suggested for use in injury assessments because natural mortality of glochidia is expected to be relatively high. For example, contaminant concentrations resulting in 100% mortality of glochidia ($\geq LC_{100}$) translate to zero production of juveniles and missing age class(es), which would directly affect the mussel population. Concentrations resulting in lower mortality rates of glochidia (e.g., LC_{80}) may translate to juvenile production below a critical threshold for population maintenance, but the ability to translate glochidia mortality to loss of individuals in a population is difficult, and the utility of data obtained from toxicity testing with glochidia decreases as the mortality rate decreases below 100%. For juveniles, the applicability of concentrations $<LC_{50}$ to the injury assessment should be discussed with the case team. If endangered species are potentially affected by spill- or site-related contaminants, more stringent concentration-based thresholds for calculating loss may be preferred. For example, an LC_{10} suggests potential loss of 10% of individuals in a population, which can be translated to the community. If the community consists of a few individuals of listed species, 10% loss of overall mussels may represent a much larger loss of the listed species. For sublethal endpoints, translation of biomass ECs to loss of biomass is straightforward (Table 1). Translation of other sublethal endpoints to loss metrics require further consideration and discussion prior to application to an injury assessment, some suggestions are provided in Table 1. Before any toxicity testing is conducted, or previous toxicity testing data are used, the case team should discuss how measured endpoints will ultimately be applied to the injury quantification and potentially used in restoration. Because mussel injury quantification for NRDAR is evolving, there are remaining uncertainties about how to estimate losses, and suggestions in Table 1 will likely be further refined over time.

Table 1. Types of toxicity tests and measured endpoints with suggestions for translation results to mussel loss (injury).

<table>
<tr><th>Life stage</th><th>Endpoint</th><th>$L(E)C_{10} \leq [x] < L(E)C_{50}$</th><th>$L(E)C_{50} \leq [x] < L(E)C_{100}$</th><th>$[x] \geq L(E)C_{100}$</th></tr>
<tr><td>Glochidia (free) in acute water exposure</td><td>Viability ~ Mortality</td><td>Not applicable</td><td>Potentially applicable; discuss with case team</td><td>Zero juveniles produced
Translate to local population loss
Missing age class(es)</td></tr>
<tr><td>Juveniles in acute water exposure</td><td>Mortality (empty shell and shell containing decomposed tissue) plus immobility (no foot or shell movement)</td><td>Calculate % loss of individuals in local population</td><td>Calculate % loss of individuals in local population</td><td>100% loss of local population
Missing age class(es)
No reproduction</td></tr>
<tr><td>Juveniles in chronic water or sediment exposure</td><td>Biomass (total dry weight of surviving mussels in a replicate)</td><td>Calculate % loss of biomass for a given area</td><td>Calculate % loss of biomass for a given area</td><td>Calculate % loss of biomass for a given area</td></tr>
<tr><td>Juveniles in chronic water or sediment exposure</td><td>Growth (shell length and dry weight)</td><td colspan="3">Need to determine best method for converting growth effects to loss. Suggestions:
• Apply as a service-loss (e.g., for use in habitat equivalency analysis (HEA))
• Convert to biomass. Develop growth-biomass curves, combine with field data
• Convert to loss of individuals. Currently unclear if reduced growth = reduced survival and/or if reduced growth = reduced reproduction</td></tr>
<tr><td>Adults in chronic water or sediment exposure</td><td>Reproduction (measured as: gamete production, fertilization success, brooding glochidia)</td><td colspan="3">Need to determine/calculate how specific metrics equate to loss. Suggestions:
• Apply as a service-loss (e.g., HEA)
• Convert to loss of individuals
  ▪ % decrease X expected survival to adult X lifetime reproductive potential</td></tr>
<tr><td>Juveniles or adults in acute or chronic water or sediment exposure</td><td>Other sublethal endpoints (e.g., behavior, filtering, body condition, biochemical endpoints)</td><td colspan="3">Need to assess how these endpoints can equate to loss prior to applying previously collected data -or- proceeding with new studies</td></tr>
</table>

Abbreviations: [x] = measured contaminant concentration, L(E)C: lethal (effects) concentration



USGS-Columbia Environmental Research Center (CERC) Mussel Culture Laboratory (left). Flow-through diluter system used to expose juvenile mussels to zinc (right). Source: USGS-CERC

Injury Quantification – Mussel Community

Almost all NRDAR cases with potential injury to mussels will require evaluation of mussel community data. Mussel community data are necessary for determining baseline, quantifying losses from visual mussel kills, quantifying long-term mussel losses, translating results of toxicity testing as described above, and quantifying injury from remedial activity.

Mussel community data can be qualitative (species composition), quantitative (mussels/unit area) or semi-quantitative (mussels observed/unit time). Mussel surveys can be designed to quantitatively characterize species composition (i.e., richness), number of live individuals per unit area or time,[8] number of fresh dead mussels per unit time or area, other demographics (i.e., size, age and length, relative abundance, population structure), and ecological services (i.e., biomass and filtration). Quantitative data are ideal for injury assessments, but in some cases, qualitative or semi-quantitative data may be all that are available, particularly for historical data sets. Any new surveys should be designed to ensure that the data obtained meet the objectives of the injury assessments. Published survey design strategies (e.g., Strayer and Smith 2003 and Smith 2006), survey protocols, and qualified surveyors should be used for new data collection.

Determining Baseline

Gathering a history of the mussel community in and near the affected area is important for baseline determination (see community assessment tool in Dunn et al. 2020). A reference site (other similar site or data collected from the site prior to the release) can also be used to determine baseline. That is, what the mussel community would be like "but for" the release or discharge. Ideally, the reference site(s) would include the same or similar types of environmental factors as the affected area since, for NRDAR, it is important to be able to separate the adverse effects of the released contaminants from other water quality effects (e.g., non-point source runoff, urbanization, industrial use). More information on reference site selection is provided in USEPA 1994, 2002, and 2006, and Whittier et al. 2007. Data from the reference site can then be compared to data from the affected area to quantify the loss of mussels as a result of a release or discharge. Where there are a number of adverse effects and/or weather

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[8] Time is considered semi-quantitative, using catch per unit effort (CPUE).

events impacting data collection, some additional site and baseline monitoring could be helpful to support the injury assessment.

Injury Determination and Quantification from Remedial Activity

Another potential focus for NRDAR assessment is the physical effects of a CERCLA remedy on mussels and their habitat. Because freshwater mussels live burrowed in river sediments, any remedial activity that disturbs mussel habitat, such as dredging of sediments to remove contamination, placement of a cap and/or backfill, can be expected to reduce densities of mussels in the area of activity. Quantitative mussel surveys conducted prior to remedy implementation (baseline), and post-remedy are optimal for injury determination and quantification because they quantify the net change in mussels (e.g., loss of density, relative abundance, change in age class structure). During the process of post-remedy surveys, mussel subject matter experts (SMEs) should evaluate whether on-site restoration will be feasible. Trustees may also be able to use historical survey data and information, data from reference locations and/or data from similar but unremediated areas to establish the baseline. While these alternative sources of information could introduce uncertainties, they may provide the only data available. Finally, the post-remedy survey information can be used directly to model natural recovery and “no action” restoration scenarios.

Information on study planning, survey design, and implementation for remedial injury to mussels is publicly available (HRNRT 2014a, 2014b, 2014c, 2019, 2020a, 2020b).[9] The survey design methods are standardized and relevant to all mussel cases, not just those with remedial injuries. These methods are also applicable to both assessment and restoration monitoring phases. Case managers should consult with mussel SMEs on the potential applicability and scalability to smaller cases.

Injury to Mussel Habitat

There is currently limited information on injury determination from spill- or site-related contaminants impacts to mussel habitat. Conceptually, the function of the habitat is to support mussels, the injury is based on the inability of the habitat to support mussels, and the natural recovery of that habitat is determined based on the rate of recovery of the mussels. If the inability of the habitat to support mussels is determined by numerical loss of mussels, either by direct measurement (surveys) or calculation of losses based on toxicological effects of contaminants present in the habitat, injury determination would default to methods discussed above, and mussel losses could then be applied to habitat using HEA. However, for some cases, particularly for those involving physical injury to habitat, injury could potentially be quantified based solely on the amount of habitat impacted, that is habitat that has decreased ability to support mussels because of the presence of oil or other contaminants. This appears to be most applicable to cases where the habitat was known to support mussels prior to an Event, such as a delineated mussel bed. In these cases, quantifying impacts to habitat may be more efficient than quantifying mussel losses by conducting mussel surveys and comparing to baseline. For example, Newton et al. (2022) illustrates injury to mussel habitat based on the percent of the mussel bed that was smothered. Cases have also tied habitat injury to the loss of mussels by assigning a percent loss of mussels resulting from a release or discharge to the habitat. For application to cases involving contamination of mussel habitat, Trustees would like to quantify how the contaminant concentrations in the mussel habitat limit the ability of the habitat to support mussels. It seems possible that if the area affected by contamination is delineated and known to support (or historically support) mussels and

[9] It is also discussed in Newton et al. (2022) that the recovery of mussel beds (i.e., persistence of injury), as measured by the number of mussels, varies by whether a chemical release occurs directly on the bed or the edge of a bed (pp. 18-19).

measured concentrations of the contaminant are above thresholds previously shown to cause mussel mortality, the proportion of habitat with lethal contaminant concentrations could be determined and used to quantify injury as habitat loss. The mussel SMEs advise that more time and effort are needed to explore: (1) what information is needed, and (2) what information is available now that is acceptable in order to more fully support quantification of habitat loss.

Defining Mussel Habitat

A critical step in mussel assessment is focusing on the functional attributes of the habitat (i.e., what mussels need from their habitat)" (p. 427) (refers to Strayer 2008; also see Figure B-4 in Appendix B for Strayer's optimal habitat variables). Evidence of mussel presence, either living or shells, should be included in the assessment; however, the presence of mussels does not necessarily indicate optimal habitat. For example, a population skewed towards older individuals is probably lacking the habitat needed for recruitment, plus the SMEs report that mussel preferences for habitat can change over time. Focusing more on the functional attributes of mussel habitat will better incorporate the physical, chemical, and biological needs of mussel habitat. In the western U.S., for example, mussel populations are found in deep rivers and reservoirs with large fluctuations in water depth. While this may not be preferred habitat, the Strayer 2008 functional attributes seem to be present and there are thriving populations. Additional literature on mussel habitat includes Haag (2012), Steuer et al. (2008), Strayer (2003), and Zigler et al. (2008).

Ways to Identify Mussel Habitat

- Functional Characteristics of Suitable Mussel Habitat (Strayer 2008):
  - ✓ Allows juveniles to settle,
  - ✓ Provides support,
  - ✓ Is stable,
  - ✓ Delivers food,
  - ✓ Delivers essential materials,
  - ✓ Provides favorable temperatures for growth and reproduction,
  - ✓ Provides protection from predators, and
  - ✓ Contains no materials toxic to mussels.
- USEPA's Rapid Bioassessment Protocols (1999).
- Basinwide Visual Estimation Technique (BVET) method (Zimmerman 2003) in combination with EPA Protocols.

In some parts of the country, mussels are found to prefer stable areas in streams comprised of shallow riffles (<1 foot deep) and deeper runs (2-3 feet deep) characterized by moderate flows during summer low discharge periods. Stream bottoms with mixed gravel, sand and fine sediments, and low embeddedness (not compacted) are the preferred substrate types and condition. If the affected area in a NRDAR case is a smaller stream/river with soft-sediment dwelling mussels, the U.S. Environmental Protection Agency (USEPA) Rapid Bioassessment Protocols (USEPA 1999) for streams and wadable rivers may be useful. Although targeted for benthic macroinvertebrates and fishes, the habitat metrics could be applied to mussel habitat evaluation.[10] Following the protocols, each of 10 metrics has a score of 1-20 which are subdivided into four categories—optimal, suboptimal, marginal, and poor. At the end, a total score is calculated, and the score can be ranked into one of the four categories. The higher the score, the better the habitat quality. Trustees have the flexibility to use EPA's categories directly or could choose to lump them (e.g., optimal and suboptimal). However, as discussed in the restoration section, functional characteristics are important for restoration implementation. In practice, EPA's protocols could be a useful habitat quantification method in some parts of the country. EPA's protocols could also be applied to estimate baseline mussel habitat services; experts would be needed to help assign the percent services to the selected habitat types.

[10] See Dunn et al. 2020 for a critique.

ASSESSMENT: Early Identification of Restoration Opportunities

Two main NRDAR-relevant categories of restoration are primary and compensatory restoration. While primary restoration is concerned with returning injured resources and their associated services to baseline condition, compensatory restoration provides services of the same type and quality and of comparable value as those injured (see 15 CFR 990.53). Whether primary or compensatory, it is important to consider mussel restoration opportunities early in the assessment process to focus the assessment efforts and ensure that restoration is technically and economically feasible.

NRDAR practitioners are advised to replace what was lost when possible, and are cautioned against simplifying the ecosystem services provided by freshwater mussels. For example, replacing the vast suite of ecological services provided by freshwater mussels with the filtration provided by vegetative habitat is an oversimplification of the ecological services provided by freshwater mussels—including habitat bioengineering—and the complex and not fully understood role mussels play in the ecosystem. Providing alternative filtration would likely not constitute actual restoration for lost mussels.

Table 2 helps match different types of restoration techniques with injury quantification approaches. Table B-1 (Appendix B) illustrates the current knowledge of restoration opportunities based on life stage and measured endpoint. The injury endpoints, in combination with the availability of feasible restoration, help drive the selection of claim development methods that are discussed in the next section. More detailed information on restoration planning, implementation, and monitoring is provided in the final section.

Table 2. Restoration Types and Associated Injury Quantification Approaches

Type of Restoration[11]	Injury Quantification Approach
1. Propagate, culture, and reintroduction[12]; translocation[13]	**Individuals:** Quantify number/density of mussels lost for direct replacement, or compared to gains (also called uplift) through reintroduction or translocation. **Biomass:** Use directly quantified measures of observed changes in mussel biomass from field or lab studies, if available (e.g., from reduced growth, lower abundance). Or, quantify number of mussels lost and convert to biomass lost (e.g., using average body mass). Compare to number of mussels gained, converted to biomass, through reintroduction or translocation.
2. Enhance existing habitat or create new habitat (uplift can be produced from "direct" restoration of mussel habitat or "indirect" restoration of buffer/adjacent habitat)	**Direct-Individuals:** Quantify number/density of mussels lost compared to gains from mussel bed creation and/or habitat enhancement projects. Newton et al. (2008) provides landscape ecologists' patch-corridor-matrix model. Mussel beds are patches; river channels are corridors connecting patches (e.g., movement of host fish, nutrients); remaining stream bed is the matrix (areas where individuals survive, but resources might be insufficient for positive population growth). (1) Where are the patches of optimal habitat for mussels? (2) How are these patches connected?

[11] Trustees will need to evaluate whether there are any on-site issues that will require off-site restoration, including continuing contamination and capacity limits in injured area (e.g., based on study, density estimates, calculation of stable population based on life-history inputs).
[12] See Patterson et al. 2018 for additional information.
[13] Among others, biosecurity and effects on location population are important considerations in any restoration involving mussel translocation.

Type of Restoration[11]	Injury Quantification Approach
	(3) How do conditions in the watershed affect location of/connections among patches? **Direct-Habitat:** Restore, enhance, replace, and/or avoid loss of the same amount of injured mussel habitat (i.e., direct replacement, could use a multiplier). **Indirect-Individuals:** Quantify number/density of mussels lost compared to gains from creation/enhancement of surrounding habitat (Ries et al. 2016, Zigler et al. 2012, FMCS 2016 (see Issue 3)). Also, the avoided loss from predator control to protect the mussel habitat (e.g., muskrats). **Biomass:** Use directly quantified measures of observed changes in mussel biomass from field or lab studies, if available (e.g., from reduced growth, lower abundance). Or, quantify number of mussels lost, convert to biomass lost; compare to number of mussels gained, converted to biomass, through habitat creation/enhancement.
3. Improve water quality and quantity	**Quality:** Quantify number/density/biomass of mussels lost and compare to gains from water quality projects, including animal fencing, best management practices (BMPs) to manage runoff, improve oxygen levels, reduce water temperatures. **Quantity:** Water quantity improvements affect flow rate (e.g., reduce shear stress and bed mobilization) and total volume. Dam removals could be considered to improve flow of water and movement of host fish (restoration of dam "tailwater" flows for mussels and fish).
4. Propagate and reintroduce hosts[14]	**Individuals:** Quantify number/density/biomass of mussels lost for direct replacement, or compared to gains from more hosts. Efforts could include propagation and reintroduction of infested host fish, or inoculation of wild fish (see Appendix C for list of facilities).
5. Land/infrastructure improvement (can include acquisition/easements, BMPs, cultural training and centers)	**Ecological:** Quantify number/density/biomass of mussels lost and compare to gains from acquiring land (e.g., avoided loss) and activities on that land (e.g., invasive species management, predator control (e.g., muskrats)). For example, protect broodstock through acquisition/easement for future conservation (avoid development). Consider whether cattle, all-terrain vehicles (ATV), or other exclusions should be included to avoid physical harm to mussels. **Tribal Cultural:** Losses that cannot be addressed through ecological restoration may require additional study on historical uses and restoration goals. Examples include spiritual/religious practices, preserving languages, and interest in Tribal youth education, among other restoration goals. Tribal SMEs noted the use of large-sized mussels includes regalia, jewelry, and tools/dishes.

Types of Restoration Opportunities

Currently, the types of restoration opportunities for mussels can be categorized as: (1) number or biomass of mussels from reintroduction; (2) habitat creation or enhancement, including aquatic ("direct") and adjacent/buffer ("indirect") habitats that benefit multiple species; (3) improvements in water quality and/or quantity; (4) availability of hosts; and (5) land conservation and infrastructure acquisition, which can provide ecological benefits as well as human and cultural uses. Trustees should factor in the availability of information and complexity of injury quantification approaches when evaluating restoration goals and project types.

[14] See McMurray and Roe 2017 for additional information.

Needs for Restoration Scaling

Trustees have a variety of decision points to consider that can inform their restoration scaling:

- Potential for on-site restoration (extent of habitat and/or expected mussel density(ies), timing), and whether natural recovery is possible given any remedial activity[15] and current densities;
- Potential for off-site restoration (extent of current habitat and/or expected mussel density(ies), type(s) of restoration activity, expected habitat uplift and/or density(ies), timing);
- Availability of avoided loss projects (i.e., projects that prevent the loss of mussels or hosts) (current habitat and/or density(ies), nature of threat(s));Identification of hosts for affected species and increase availability of hosts (relate type and number of hosts (e.g., fish, salamanders) to a changing mussel population over time);
- Whether mussels are part of a larger aquatic injury and their biomass may better support restoration goals;
- Whether fish hosts are already being addressed as part of a fish claim (potential for double-counting); and
- Determination of whether human/cultural uses can be addressed solely through ecological restoration or require additional economic study (e.g., through a survey).

> ***Regulatory Context for Mussel Assessment***
>
> It is important to remember that while Trustees have options to pursue a NRDAR claim, there are statutory and regulatory constraints. 43 CFR 11.80(b) clarifies that "the measure of damages is the cost of:
>
> (1) Restoring or rehabilitating the injured natural resources to a condition where they can provide the level of services available at baseline, or
>
> (2) Replacing and/or acquiring equivalent natural resources capable of providing such services."
>
> Damages can be measured by an appropriate combination of partial restoration or rehabilitation, and partial replacement and/or acquisition of equivalent resources, so long as there is no double counting. Trustees can choose to directly restore mussels to baseline or engage in modeling efforts that would include interim losses (e.g., HEA, REA).
>
> Because of the uncertainties on the best ways to incorporate freshwater mussels in NRDAR cases, Trustees should keep the regulatory criteria in mind while innovating. "The authorized official shall determine that the following criteria have been met when choosing among the cost estimating and valuation methodologies…
>
> (i) That are feasible and reliable for a particular incident and type of damage to be measured.
>
> (ii) That can be performed at a reasonable cost, as that term is used in this part.
>
> (iii) That avoid double counting or that allow any double counting to be estimated and eliminated in the final damage calculation.
>
> (iv) That are cost-effective, as that term is used in this part" (43 CFR 11.83(a)(3)).

Issues with Quantifying Uplift from Buffer/Adjacent Habitat Restoration

Some studies suggest that mussel declines in certain systems are related to adjacent land use practices like agriculture and development, resulting in siltation, sedimentation, and turbidity (e.g., Hornbach et al. 2019, Randklev et al. 2015, Arbuckle and Downing 2002, Henley et al. 2000). Haag (2019) cautions that the reasons for mussel declines are largely untested and the lack of robust scientific data hinders the ability to understand the reasons for their decline (also see Tuttle-Raycraft and Ackerman 2019/2020, Haag 2012, Hoch 2012, Gangloff et al. 2011, Strayer and Fetterman 1999).

[15] This assumes remediation is sufficient to eliminate, not just reduce, toxicity to mussels and that other, noncontaminant-related stressors will not limit mussel recovery.

Henley et al. (2000) recommends installing exclusion fences to keep livestock out of riparian areas and revegetating riparian zones to reduce agricultural input of sediment into lotic environments. These types of BMPs were part of the South River NRDAR case claim, but the gains to mussels were not explicitly quantified.

At this point in time, there are no published data that provide guidance on how to quantify uplift to mussels from buffer/adjacent habitat restoration. Trustees should carefully consider whether buffer/adjacent habitat restoration is the best choice. If there is a need to explicitly credit the gains to mussels from buffer/adjacent habitat restoration, NRDAR practitioners may want to consider using HEA, the metric of clearance rates (i.e., the volume of water cleared of particles; see Appendix D), and/or a pilot study.

ASSESSMENT: Damages Determination

Damages determination relies on the case economist's understanding of: (1) how the Trustees are defining the loss of mussels (e.g., loss of individuals, community, density, or % service), and (2) which restoration techniques the Trustees are using to restore those losses. The total area of mussel habitat (by type, e.g., optimal, marginal) multiplied by mussel density (by habitat type) is assumed to give the total local population.[16] Mussel SMEs can also provide input on the quality of the total local population (e.g., importance of species richness, relative abundance, age structure). The SMEs recommend identifying whether species-level plans have been developed, which may include recovery goals and strategies, for use in restoration scaling and damages determination.

Table 3 summarizes the current universe of damages determination approaches. Each cell identifies an option for the NRDAR case manager. For example, *1A* identifies the resource equivalency analysis (REA) method may be used to build a claim that has mussel propagation and reintroduction as the restoration (see Figures B-1, B-2, and B-3 in Appendix B). However, *1C* shows that habitat equivalency analysis (HEA) is not the proper method for mussel reintroduction. While % mussel losses and % mussel gains would be good metrics to develop a HEA, the scaling would more appropriately be in habitat improvement (*3C*), water quality/quantity improvement (*4C*), or land acquisition (*5C*).[17] Trustees have the discretion to replace what was lost and not pursue interim losses. *1F*, *2F*, and *4F* could be developed using direct replacement (1:1) or a multiplier on the losses.[18] Life history could be used on the losses and/or crediting, but there would be no discounting and the metric would be in mussels or hosts.

Human/cultural use losses that cannot be adequately addressed through ecological restoration may require additional study on historical uses and restoration goals (e.g., *5D*). Efforts could include discussions with Tribal Elders, use of focus groups, and various types of surveys, among others.[19]

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[16] # of mussels = m^2 of mussel habitat (per type of habitat like optimal, marginal) x mussel density per type of habitat (# mussels/m2). Practitioners should be aware that unless surveys were designed to provide unbiased estimates across entire stream/river reaches, this extrapolation will introduce uncertainty.

[17] See Newton et al. (2022) for an applied mussel HEA. Dunn et al. (2020) created a mussel community assessment tool (MCAT) for the Upper Mississippi River System that uses five categories of scoring metrics: (1) conservation status and environmental sensitivity, (2) taxonomic composition, (3) population processes, (4) abundance, and (5) diversity. The metrics were validated using a modified Delphi technique. The methods could be useful to NRDAR case teams interested in developing a relatively robust HEA.

[18] For example, 100 mussels were killed by a release of hazardous substances and 100 propagated mussels are reintroduced to replace the losses (1:1). A multiplier could be based on the survival rate of reintroduced mussels, so more mussels should be reintroduced to actually achieve 1:1 replacement.

[19] For more information, see: https://www.doi.gov/ppa/nrdar-tribal-cultural-resources-project

Trustees may find new research by Hoelting et al. (2022) helpful with the incorporation of decision-making processes to include Indigenous Knowledge.

There are a number of "?" in Table 3, which reflect the evolving state of the science and NRDAR practice. Case managers should work with mussel SMEs, case solicitors, and case economists to help determine best available methodologies to address unique case needs.

Economists' Tips on Mussel REAs

If at all possible, developing a mussel REA using the net change in mussel density for the debit and credit is ideal. The information needed includes:

- Baseline mussel density per habitat type(s)
- Current and projected mussel density per habitat type(s) (e.g., impaired by contaminant(s), loss from remedial activity)

The difference between the current/projected and baseline densities results in the loss. The discounted loss of annual density is applied to the total injured area to estimate the REA debit. Crediting is calculated based on the improvement in discounted annual density over time from restoration activities.

The annual density already reflects the local population dynamics, so additional life history information (survival rates, lifespan, reproduction) is not needed.

The timing of the mussel losses and restoration gains, and the rate of restoration gains, will need to be evaluated.

Table 3. Overview of Current Damages Determination Methods that May or May Not Be Applied to Restoration Types, Including Uncertainty

Methods / Restoration Types[20]	1. Propagate and Reintroduce Mussels	2. Habitat Improvement	3. Water Quality Improvement	4. Propagate and Reintroduce Host Fish	5. Land Acquisition/ Infrastructure[21]
A. Life History/Density Resource Equivalency Analysis (REA)	Yes	Maybe (direct and indirect (e.g., adjacent/buffer))	Yes?	Yes, for some mussel species with known hosts	Yes (avoided loss and enhancement)
B. Biomass REA (also called HaBREM)	Maybe?	Yes (direct) and Maybe (indirect (e.g., adjacent/buffer))	Maybe?	Yes, for some mussel species with known hosts	Maybe?
C. Habitat Equivalency Analysis (HEA)	No	Yes (direct and indirect (e.g., adjacent/buffer))	Yes (direct and indirect (e.g., adjacent/buffer))	No	Yes (avoided loss and enhancement)
D. Tribal Cultural Uses	Yes (more resources, potential for facilities)	Yes (more resources)	Yes (more resources, potential for facilities)	Yes (more resources, potential for facilities)	Yes (more resources, potential for facilities)
E. Other Human Uses (e.g., shell, pearl markets (Strayer 2017)	Yes	Maybe?	Maybe?	Maybe?	Maybe?
F. Direct replacement, multiplier (no interim losses)	Yes	Yes	No?	Yes	Maybe?

The relevant metrics/units for the methods, indicating the types of information needed, include:

- % services (HEA)
- mussel density/abundance (HEA, REA, Tribal cultural, direct replacement)
- spatial (river-miles, m^2, acres) (HEA, REA, Tribal cultural, replacement)
- grams/kilograms (biomass REA, Tribal cultural, replacement)
- time (e.g., post-cleanup recovery, restoration recovery, longevity of mussel beds[22])
- types and frequency of uses (Tribal Cultural, other human uses)
- $ (restoration costs, market value of other human uses)

See Table B-2 (Appendix B) for the injury quantification methods based on the affected life stage and injury endpoints.

[20] See Newton et al. (2008); includes food and protection from predators.
[21] Can include easements, BMPs, cultural training (language, youth education) and supporting cultural infrastructure like Tribal cultural centers, mussel/fish host propagation facilities, etc.
[22] See Sansom et al. (2018).

Restoration Cost Estimation for Damages Determination

As experienced NRDAR practitioners know, restoration costs vary by project type, location, and timing, among other factors. There are three basic categories for which costs should be estimated: (1) contracted/cooperative agreements; (2) Trustees' costs on actual implementation (e.g., Department bureau staff costs to collect broodstock, stock mussels, conduct monitoring); and (3) Trustees' **R**estoration Planning, and **I**mplementation and **M**onitoring Oversight (RIM) costs (e.g., costs for Trustees to coordinate, manage contracts, check on implementation progress, and review monitoring reports). While estimation of an average cost per mussel is improving with the increasing number of freshwater mussel NRDAR case assessments, at this time it is still recommended to develop case-specific restoration cost estimates.

Table 4 provides a checklist of potential restoration cost categories to help facilitate discussion on restoration cost estimation. Consult with your mussel and restoration SMEs, case solicitors and case economists, as well as ORDA's Restoration Support Unit (RSU), for additional guidance. The USFWS Cost Estimation Tool (CET) is available for all Departmental bureaus to consistently develop a summary of restoration cost estimates that appropriately incorporate inflation over time (contact ORDA or USFWS Headquarters). Please note that at this time, SMEs have advised that hatchery-focused costs, such as presented in Southwick and Loftus (2017), are not comprehensive enough for damages determination.

RESTORATION: Planning

Identifying restoration opportunities early in the assessment phase facilitates injury quantification and restoration scaling (Table 2). Over the course of the assessment, additional information may become available that alters restoration opportunities and quantities that were identified earlier in this phase. The revised restoration options could be relatively simple or may evolve into complex and comprehensive projects that require careful consideration during the restoration phase. Additional support from restoration SMEs may be needed. Including SMEs through all phases of the restoration may save on implementation and monitoring costs by reducing time spent in adaptive management cycles.

Restoration Goals

A sometimes overlooked and critical first step of any restoration project, clear goals and objectives should be determined before any active restoration occurs. This restoration planning phase should be differentiated from the early discussions of restoration opportunities and Trustees' goals.[23] Restoration goal setting includes:

- Setting expectations,
- Preparing detailed plans for actions, and
- Determining the types and extent of project monitoring.

To best identify restoration goals, Trustees should consider conservation targets and ecosystem services. Goals for conservation targets might focus on the viability of one or more populations for conservation purposes.

[23] Cost-effectiveness means choosing the restoration that meets Trustees' goals at least cost, not just the least costly restoration option. See 43 CFR 11.14(j).

Table 4. Checklist of mussel and host restoration cost categories

Propagation ☐ Labor (includes propagation plan, implementation for broodstock/propagated, reporting) ☐ Field and lab materials/supplies/gear (e.g., nets, waders, tagging) ☐ Equipment (broodstock repository/genetics, culture, rearing systems) ☐ Vehicles/travel (e.g., collect broodstock, translocation)(local vs. non-local) ☐ Overhead/indirect costs (actual supporting costs, not contingencies)*	**Habitat Restoration/BMPs** ☐ Labor (includes planning, design, implementation) ☐ Materials (e.g., gravel, trees, fencing/supplies/gear) ☐ Equipment (e.g., gravel shooter) ☐ Vehicles/travel (local vs. non-local) ☐ Overhead/indirect costs
Release/Reintroduction ☐ Labor (includes release plan, implementation, reporting) ☐ Materials/supplies/gear ☐ Field equipment (transport) ☐ Vehicles/travel (local vs. non-local) ☐ Overhead/indirect costs	**Land Acquisition/Easement Purchase** ☐ Labor (transaction time, government realty SMEs (e.g., Refuges, State), Land Trust) ☐ Land/easement price ☐ Fees**/travel (local vs. non-local) ☐ Overhead/indirect costs

Monitoring (traditional, eDNA; sample analyses)
☐ Labor (includes monitoring plan, implementation, reporting)
☐ Materials/supplies/gear
☐ Field equipment
☐ Lab equipment (eDNA)
☐ Vehicles/travel (local vs. non-local)
☐ Overhead/indirect costs
	New Infrastructure
	☐ Land acquisition (see above) or lease
	☐ Planning/Pre-Design/Permitting
	    ☐ Design
	    ☐ Lab space
	    ☐ Office space
	    ☐ Grow-out ponds/fish raceways
	    ☐ Outbuildings
	    ☐ Security (e.g., fence, gates, lights)
	    ☐ Water supply/transport
	    ☐ Quarantine area/facilities
	☐ Construction, materials/supplies
	☐ Overhead/indirect costs

Biosecurity (risk reduction of disease) ☐ Labor (includes plan development (if none exists), training, auditing) ☐ Sample analyses ☐ Supplies (e.g., foot baths, disinfectant) ☐ Overhead/indirect costs	**Trustees' RIM** ☐ Draft restoration plan and environmental compliance (includes permitting) ☐ Final restoration plan ☐ Public communication/outreach ☐ Trustee Council administration (i.e., Trustee council resolution, administrative record maintenance) ☐ Implementation oversight ☐ Monitoring oversight
**Overhead/indirect costs can include rent, utilities, insurance, office supplies, taxes and fees, etc. These are actual supporting costs and should not be confused with contingencies.* ***Fees may include legal costs, appraisals, environmental assessments, etc., which are often lumped as "due diligence."*	**Contingency** ☐ Contact ORDA for guidance (2022) to DOI NRDAR practitioners on the development and application of contingencies.
	Contracting Other than Trustees' RIM, all of these categories could be contracted. Contracted costs include overhead, profit, contingencies, and performance bond, among others. While Trustees can request itemization, many of these costs will be built into the estimates.

Goals for ecosystem services might focus on the restoration of one or more desirable ecosystem services (Strayer et al. 2019). Trustees could attempt to meet both conservation target and ecosystem service goals, but feasibility considerations and varied assessment approaches might make this approach challenging. If the purpose of the restoration project is to increase ecosystem services, then these services or underlying ecosystem functions should be included in project goals and monitored (see Monitoring discussion below).

Restoration Objectives

Whereas restoration goals are often broad statements about what a restoration action seeks to achieve, statements on the restoration objectives are much more specific. Clearly defined restoration objectives will describe what the restoration action is seeking to accomplish, and the desired state of the restored ecosystem. NRDAR practitioners may find Gillies (2019) useful for setting objectives for each discrete restoration action. **S.M.A.R.T.** objectives (**S**pecific, **M**easurable, **A**ttainable, **R**elevant, and **T**ime-bound) include:

- Attributes being measured,
- Desired outcome (e.g., increase, decrease, maintain),
- Magnitude of effect, and
- Timeframe.

Well-defined objectives will help inform selection of the most effective indicators (metrics) to monitor restoration activities. These are often called performance criteria, as described in the next section.

Restoration plans should use the same functional attributes for habitat (i.e., what mussels need from their habitat, Strayer 2008) identified during the assessment (Figure B-4, Appendix B) to assess criteria for a successful outcome before implementation. Restoration SMEs advise that practitioners may find it helpful to use Gann et al. (2019; Figure 3) to organize the mussel-specific attributes into these bins of ecosystem attributes, which can be used for all restoration types:

- Absence of Threats: testing water quality; predator/invasives surveys
- Ecosystem Function: year-round presence of mussel dietary needs
- Species Composition: adequate age/density of host fishes
- Physical Conditions: substrate stability surveys
- Structural Diversity: mussel optimal habitat surveys
- External Exchanges: evaluate health/condition of adjacent ecosystems

Restoration Metrics

Restoration planning and monitoring are ideally accomplished using the metrics used for the damages determination (e.g., number of mussels expected per m^2) and additional metrics used for monitoring other ecosystem attributes contributing to the restoration, as guided by Gann et al. 2019. Expected outcomes are ranked as short-term goals that determine progress for the individual tracking factors of each ecosystem attribute (discussed below), and will contribute to the achievement of overall restoration goals and objectives. Specifically:

- Restoration options were identified early, and likely were filtered or refined during the assessment.
- The restoration goals and objectives were guided by the metrics and scaling results, all of which will contribute to determining progress when monitoring restoration.

Performance Criteria

Performance criteria describe the desired observable and/or measurable results of the restoration action(s) and tie back to project objectives. Given life history traits such as longevity, high juvenile mortality, and sensitivity to disturbance, monitoring of mussel populations will likely need to extend for >10 years and could be intermittent in timing (Strayer et al. 2019). For these reasons, longer-term performance criteria are critical to evaluate progress toward desired ecosystem, community, and/or population conditions.

The ecosystem attributes have numerous influencing factors and deterministic variables that can be used as performance criteria and for tracking over time ("tracking factors"). These tracking factors are represented as the smaller wedges in the restoration/recovery wheel in Figure 3, and incorporate five levels/stages of actions that contribute to restoration/recovery. Some tracking factors may begin at relatively high levels in the post-remedy stage similar to the contamination and water chemo-physical tracking factors (at level 4) in Figure 3, while other factors in the severely injured attributes (i.e., ecosystem function and structural diversity) are lower and will require more time and effort (steps) to achieve restoration.

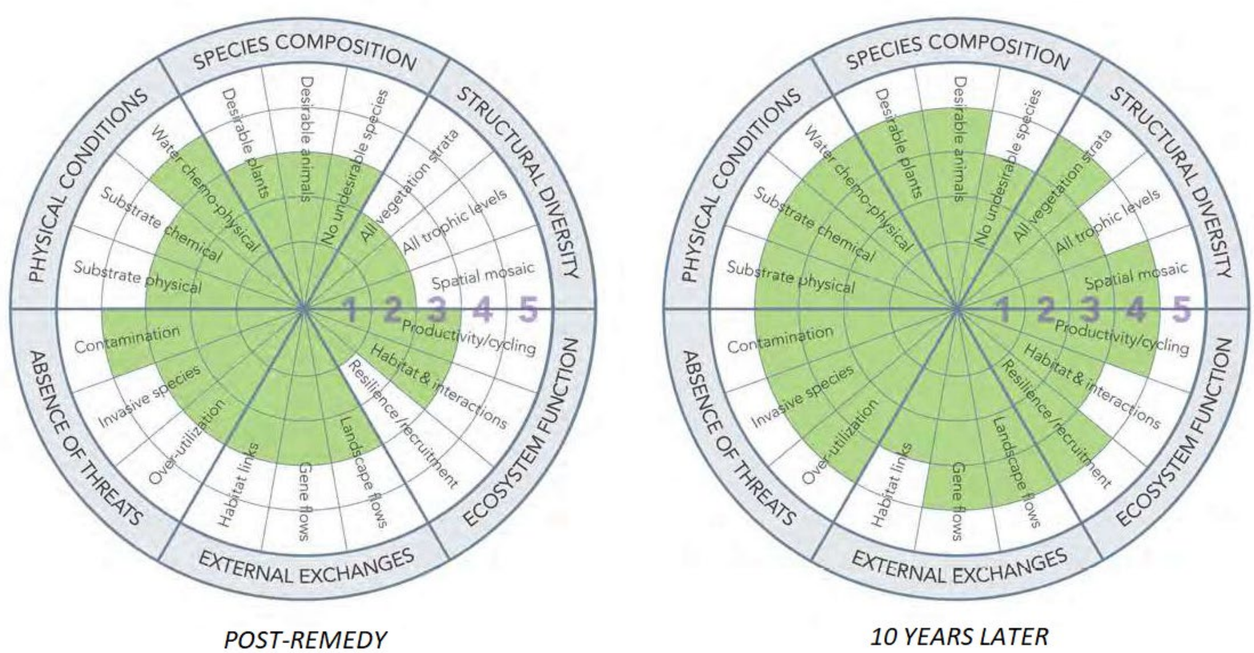

Figure 3. Restoration/recovery tracking wheels (modified from Gann et al. 2019)

Figure 4 provides examples of each key ecosystem attribute to be evaluated during restoration planning. These should be considered during development of performance criteria and success measures, and ultimately incorporated into monitoring. Restoration SMEs can help identify factors and possible outcomes for specific ecosystem attributes when planning restoration objectives, and in writing or reviewing the restoration plan.

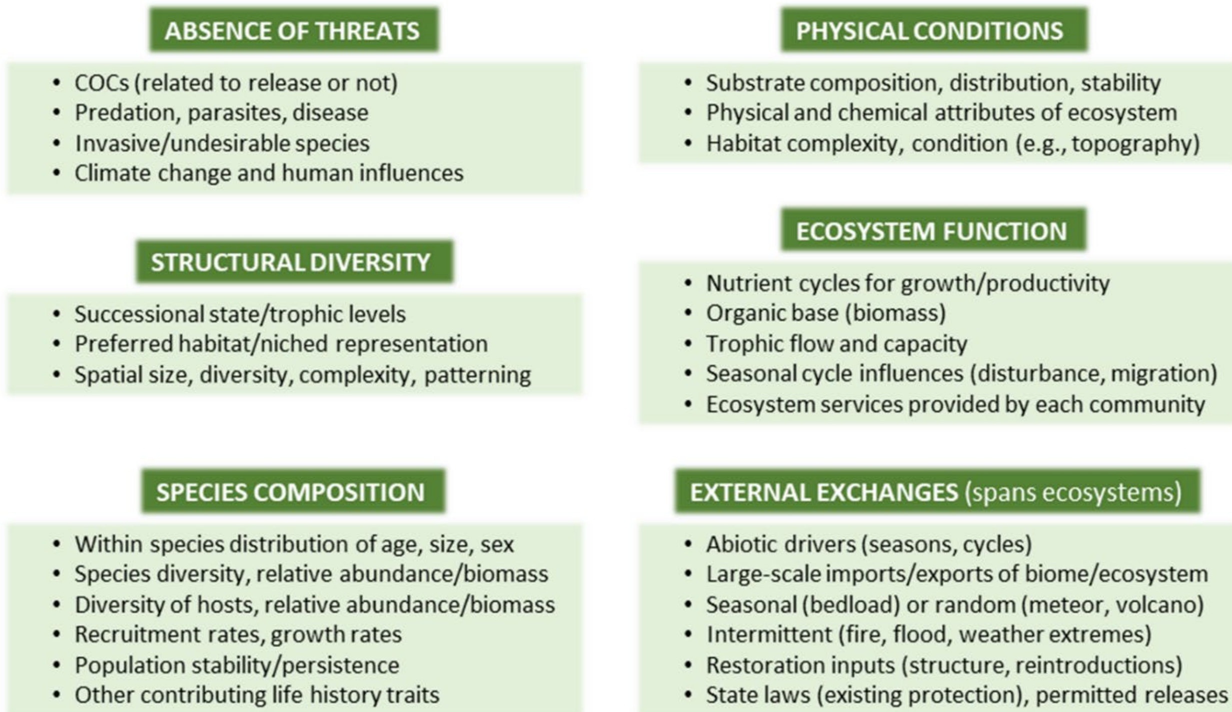

Figure 4. Tracking factors for each key attribute to consider for performance measures in restoration planning

Planning for Successful Restoration Outcomes

Restoration in sites having previously supported assemblages may support restoration efforts with an immediate uplift. However, all restoration sites should ensure that contaminants causing toxicity to mussels are not present or have been eliminated (e.g., through remediation), and that other stressors (e.g., drought/flooding, polluted runoff, predation, invasives) will not perpetually hamper mussel recovery, and have been evaluated and controlled, if necessary. Pilot studies may be required before restoration is implemented to explore technical feasible of the restoration action and location. (Gray and Kreeger 2014, Kreeger et al. 2018).

Although "Absence of Threats" is one of the ecosystem attributes to consider when evaluating restoration options throughout the case, the reality is that all restoration efforts face threats and risk failure at any point in time. Because of these natural risks and uncertainties, some considerations for successful planning include:

1. Assemble a qualified planning team with SMEs (having a diversity of knowledge, skills and experience) from partner agencies, institutions, and organizations who will contribute to the planning, implementation, and monitoring processes. Consult respective recovery specialists if restoration involves federal or state endangered/threatened species – existing recovery plans and expertise will prove valuable in all restoration stages/processes.
2. Include appropriate metrics, strategies, quality assurance/quality control, pilot tests, monitoring, alternatives/contingency plans, and adaptive management practices (e.g., Gann et al. 2019).

3. Determine the timeframe for achieving restoration endpoints; whether the restoration objectives will be achieved in a single phase in a short time period or multiple phases over several years. Short-term goals with stepwise review and modifications can provide successful minor outcomes leading towards the overall restoration objectives.
4. Identify teams, contractors, project managers, permitting agencies, etc., for each project early in the planning stages, and their respective roles and responsibilities.
5. Verify that budgets are adequate to cover all phases of restoration, including realistic contingency costs to cover adaptive management revisions and inflation, through restoration monitoring to completion of the restoration goals and objectives.
6. Include performance criteria over the project timeline to verify that phase-dependent tasks are on track, particularly for complex projects.
7. Include appropriate suite of restoration alternatives in the restoration plan that is evaluated pursuant to the applicable NRDAR regulations.
8. Develop appropriate and timely public outreach on the restoration project(s).

RESTORATION: Implementation

Each State has a mussel program with focal species for specific rivers and assemblages; these programs are primarily focused on mussel recovery. Although information and lessons learned concerning mussel recovery exist, they are not NRDAR-specific, and needs of NRDAR cases may not match that of recovery programs. Considering the complexities of mussel life cycles, lotic ecosystems in general, and recent interest in restoring these critical ecosystem components, this discussion of mussel restoration strategies cannot be exhaustive. Assumptions, guidelines, and recommendations will need to be revisited in the context of new scientific developments, and project- or taxon-specific experience. Acknowledging these limitations, the following discussion is derived from extensive exploration and aggregation of SMEs' professional judgments and the existing body of freshwater mussel literature,[24] as well as relevant research concerning other bivalves, to describe a basic structure for practitioners to consider for freshwater mussel restoration.

Implementation Strategies

As discussed in previous sections (ASSESSMENT: Damage Determination), the overarching aim of restoration in the NRDAR context is to restore, rehabilitate, or replace the injured natural resource—*or its equivalent*—such that the resultant resources or services acquired from restoration actions are at comparable levels to those existing under baseline conditions. Restoration may be expressed in number of individuals or outputs from economic analysis (e.g., discounted mussel-years (DMYs)), community metrics, density, or % service, and could include a spatial context that is typically quantified in m^2, hectares/acres, or river-miles of restoration.

In contrast to a sole focus on achieving similar assemblage- or ecosystem-level structure (e.g., taxonomic and/or guild distributions) of some non-NRDAR restoration efforts, NRDAR restoration provides practitioners with some flexibility in choosing restoration actions that adequately address specific goals (e.g., which services to restore, how many mussels to replace) and achieve suitable endpoints (e.g., what levels of services are acceptable). Even if relative abundances of specific species

[24] Existing guidance concerning best practices for restoration implementation is sparse (Haag and Williams 2014). See CRMRC 2010, Miller and Lynott 2006, and Patterson et al. 2018 for information on mussel recovery and restoration.

within a restored assemblage are dissimilar to those existing at baseline, such an assemblage may still provide equivalent services to baseline conditions (Haag and Williams 2013, Vaughn 2017).

In practice, passive and active techniques will typically be used in some combination to achieve mussel restoration.[25] Drawing on the restoration and recovery literature, as well as the experience of mussel SMEs, the following are current best practices for mussel restoration implementation:

1. *Understand stressors*—From the earliest discussions of restoration opportunities, mussel SMEs will identify non-contaminant stressors in the affected area as confounding factors. The restoration planning will seek to understand the stressors and minimize them as appropriate through other restoration activities (e.g., runoff control, animal fencing) and/or selection of restoration sites (on-site or off-site). It is obviously ideal to minimize stressors during restoration (i.e., contaminants both directly related or unrelated to the injury, and biological stressors (e.g., invasives, predators, parasites, and disease)). However, the mussel SMEs advise that it is *not* possible to alleviate *all* stressors. Within the NRDAR framework, Trustees may be able to address some stressors through restoration, but others may exist (i.e., residual contamination in sediment post-clean up) or emerge that will continue to exist. As an illustration, the Clinch River in Virginia includes a stretch of river within an active coal mining region that is likely not suitable for mussel restoration. However, mussels are thriving 10 miles upstream of the mining impacts. From the perspective of the Clinch River NRDAR case, although there are ongoing stressors from mining, opportunities for restoration exist.[26]
2. *Identify and Seek to Minimize Risks and Uncertainties*—Consistent with the philosophy of recovery programs to "do no harm" (Blevins et al. 2019), mussel SMEs advise that Trustees should seek to minimize uncertainties and concerns in NRDAR restoration. Mussel restoration actions in the field and laboratory need to be carefully planned to minimize risks to taxa and habitats. Critically, monitoring data can be used to gauge restoration success or failure and will allow practitioners to adaptively manage their restoration activities.
3. *Enhance Environmental Quality*—Implement management actions that improve habitat, flow-regimes, and water quality to promote sustainable assemblages, and improve recruitment success (Ries et al. 2016), especially where source populations and dispersal mechanisms will function (Beechie et al. 2008, Newton et al. 2020). However, in cases with severe habitat and/or water injury, mussel and/or host species translocation or reintroduction may be ineffective (see #4).
4. *Management of Biota*—Direct management of mussels and/or their host organisms is possible and has been done with varying success. Historically, translocation of mussels or hosts from other stream reaches was the only viable option for stocking efforts. Recent advances in propagation make *ex situ* sourcing of mussels from rearing facilities a viable option for restoration, including the evolving use of *in vitro* techniques. The mussel restoration literature includes three categories: (1) reintroduction of locally extirpated mussels, (2) introduction of mussels to habitats where historical presence has not been verified observationally, but that has habitat-characteristics amenable to mussel establishment, and (3) augmentation of extant but reduced populations. Mussels for these restoration techniques have been sourced from translocated wild populations or facility-propagated populations. However, these approaches are not without risks such as disease spread and dilution of genetic factors (Hoftyzer et al. 2008,

[25] An example of a post-settlement mussel restoration implementation strategy document will be available in Appendix D. Placeholder text with contact information is provided for now.
[26] Personal communication, Dr. Jess Jones, USFWS, September 22, 2022. For more information on the Clinch River mussel restoration, see Hyde and Jones (2021).

Strayer et al. 2019, McMurray and Roe 2017). Thus, it is important that the Trustees *collaborate with malacologists and other technical experts and State regulatory bodies,* and conduct a thorough evaluation of *relative risk* by the restoration actions prior to choosing a technique (and source (propagation-facility vs. translocation). To date, NRDAR cases with restoration of propagated mussels (e.g., Clinch River, Lone Mountain, South River) have involved augmentation of reduced populations. As discussed briefly above (ASSESSMENT: Early Identification of Restoration Opportunities), there are mixed views on translocation, including biosecurity and detrimental effects on local population, among others. Translocation may be unsuitable for rare taxa because the source population cannot withstand removal, but may be viable for common taxa with proper screening. Acknowledging these issues, translocation may be the only option in some critically endangered contexts if a species has not been previously propagated. Anecdotally, mussel SMEs have noted that threatened and endangered mussel species tend to have propagation programs, with little to no investment in propagating more common taxa. NRDAR cases may need to fund expanded propagation programs if very large numbers of common mussels are needed for restoration.

RESTORATION: Monitoring

The following provides a broad overview of restoration monitoring approaches as they relate to restoration projects, including reintroduction, augmentation, and habitat enhancement. Monitoring is particularly essential to identify release locations and quantify the success of any restocking effort over time. Monitoring goals can be centered around ecosystem services provided by freshwater mussels, including supporting services such as nutrient recycling and storage, structural habitat, substrate and food web modification; regulating services such as water purification; and/or cultural services including use as a food source, tools, or jewelry (Vaughn 2018). Specific monitoring objectives could include: (1) document the recovery of habitat, density, age structure and/or species composition; (2) estimate

Monitoring released mussels using passive integrative transponders (PIT) tags.[27] Quantitative monitoring can be used to determine survival, growth, movement and migration. Source: USFWS

[27] Overview of mussel tags and tagging methods available, e.g., in: https://molluskconservation.org/Library/PROPAGATION%20PDFs/Mussel%20tagging%20methods_2015.pdf and Cheng 2017.

survival, growth, reproduction, and movement of hatchery-reared mussels; and/or (3) estimate habitat metrics relevant to re-establishing mussel populations, such as sediment stability (Zigler et al. 2012, Morales et al. 2006, Sansom et al. 2018).

Monitoring to Evaluate Restoration Performance and Outcomes

Restoration projects should be monitored to evaluate progress and determine whether restoration objectives are being met. For complex restorations (e.g., those requiring multiple concurrent projects), it is important to compare across projects to assess programmatic and/or regional level outcomes and to characterize the variability of restoration impacts across project areas. Monitoring assesses and enables management of the progress of project activities and defines the degree of success at the cessation of those activities. Since a comprehensive review of monitoring freshwater mussel restoration projects is not the focus of this section, the reader should refer to other sources and SMEs (see Figure 5, Hooper et al. 2016; Blevins et al. 2019).

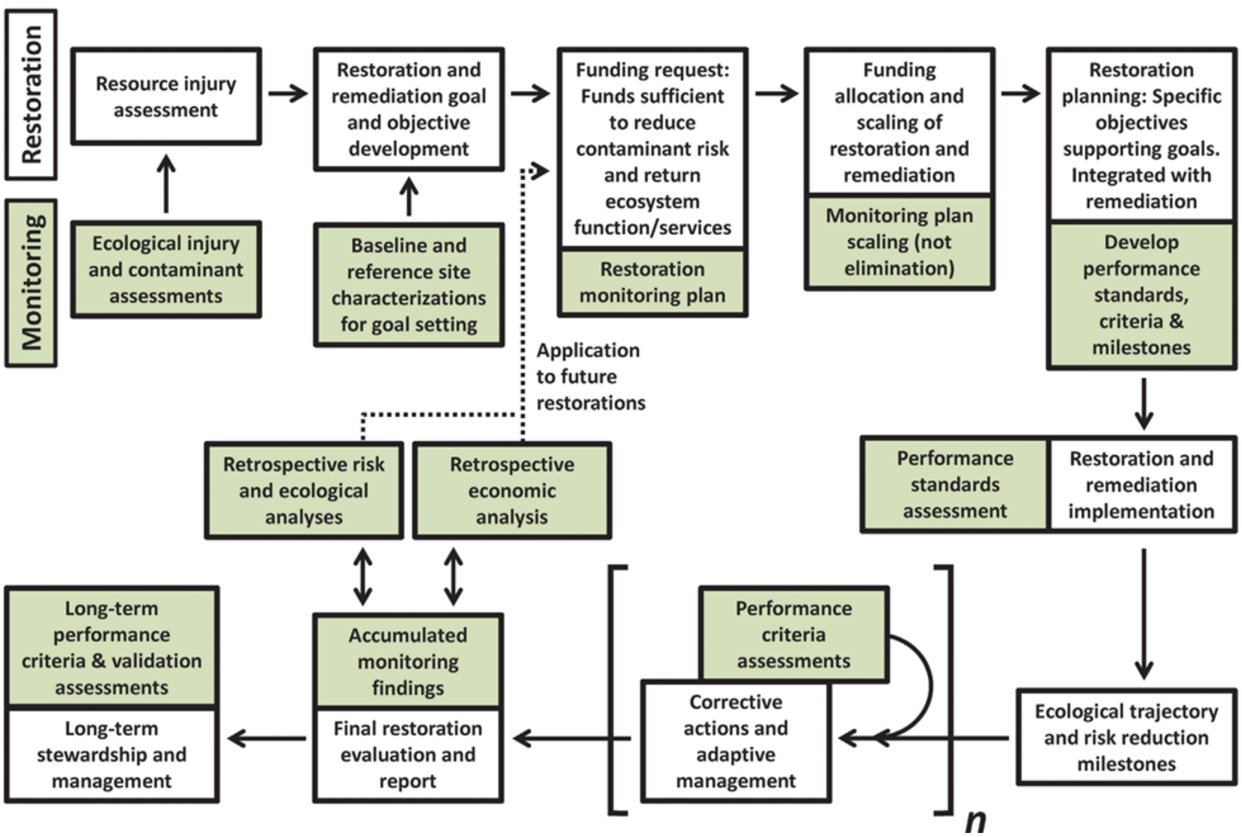

Figure 5. Application of monitoring to the ecological restoration of contaminated sites. Monitoring provides inputs into planning (separate monitoring boxes) and then integrates into the restoration and/or remediation process (fused boxes). When not specifically noted, remedial actions continue concurrently with restoration. "n" is the number of iterations necessary to maintain restoration trajectory toward restoration and remediation goals, and varies with project complexity, duration, and resources. (Hooper et al. 2016, with permission)

Types of Monitoring

Restoration practitioners should understand that monitoring falls into three general categories: (1) implementation, (2) effectiveness/performance, and (3) validation/monitoring for adaptive management (see MacDonald et al. 1991: 6-8; Roni 2005 for more information). Specifically:

- **Implementation monitoring** is used to confirm that the project was implemented according to the approved designs, plans, and permits. Essentially, it determines whether the agreed upon work was completed as planned and meets performance standards. Performance standards are methodologies and materials deemed appropriate to meet the project objectives.
- **Effectiveness/performance monitoring** is used to determine whether restoration was effective in attaining desired objectives and meeting performance criteria. Effectiveness monitoring can be either qualitative or quantitative, although quantitative is typically preferred.
- **Validation/long-term monitoring** can be used to verify basic assumptions behind effectiveness monitoring and to evaluate adaptive management actions. Specifically, adaptive management involves analysis of monitoring results to identify potential problems occurring in restoration areas and to determine and implement measures aimed at rectifying such problems to increase likelihood that the project will reach its original goal (Hilderbrand et al. 2005). Monitoring should continue while restoration progresses, and Trustees should undertake adaptive management activities that keep the project on course until structural or functional metrics suggest attainment of, or a solid trajectory toward achieving, final restoration goals.

For all mussel monitoring, metrics should be recorded in the field and every effort should be made to minimize stress to mussels (Strayer and Smith 2003). Mussels monitored should be returned to the river in the collection area or immediate vicinity of as soon as possible after collection.

Recommended Monitoring Metrics

For purposes of NRDAR, the selected restoration monitoring metric(s) should relate back to the injury assessment, such as factors used to define loss of mussels as a result of a release (e.g., number of individuals, community metrics, density, or % service). Of the universal monitoring metrics provided in Table 5, at least one biological monitoring metric should be selected for the mussels or hosts, depending on project focus, along with the environmental indicators. Most projects should monitor the size and demography of the target mussel population over a spatial extent to be influenced by the implemented project, and over a spatial extent that can be effectively sampled and defined. Mussel host organisms should also be monitored if the project target is to increase their presence. Selection of environmental indicators should be informed by both stressors to mussels, as well as expected outcomes of the restoration project, such as direct or indirect improvements to water quality and/or habitat enhancements that will benefit mussels (i.e., riparian corridor improvements, reduced run-off, cattle fencing/alternative water source). Monitoring likely will need to occur for many years, given the long generation time of mussels (years to decades) and the high temporal variability of mussel population and assemblage dynamics. For cases with pre- and post-remediation, or post-release, surveys that include density and variance metrics, it may be possible to develop a predictive model to estimate the needed monitoring frequency sufficient to detect trends in population changes attributable to restoration actions (Strayer and Smith 2003, Green and Young 1993, Smith et al. 2001). Mussel SMEs and statisticians should be consulted for cases that would be benefit from this level of rigor.

Table 5. Suite of universal monitoring metrics for freshwater mussel or host restoration projects

Metric	Example	Comments	References
Physical Habitat Indicators (Environmental)	Various habitat indicators (e.g., channel morphology, sediment stability - TSS/SSC*)	Hydraulic measures (shear stress, substrate stability) predict mussel distribution and abundance better than simple variables (e.g., discharge, particle size)	Morales et al. 2006, Steuer et al. 2008, Zigler et al. 2008 *Total Suspended Solids/Suspended Sediment Concentration
Water Quality Indicators (Environmental)	Various water quality indicators (e.g., pH, temperature, O_2, CO_2, contaminants)	Commonly monitored water quality parameters, to those requiring specific analytical techniques (site dependent)	Geist and Auerswald 2007, Allan and Vaughn 2010, Goldsmith et al. 2021
Total Individual Mussels	Number of individuals (mussels or hosts)	Observed change in total number of individuals over a defined area. Often tied to population structure (below).	Many references, but Strayer and Smith 2003 is the most extensive reference (pp 64- limitations of timed search, and methods for very small streams where full coverage is possible. See also, Hart et al. 2016 (recent review) and Wisniewski et al. 2013 (complicating factors). https://molluskconservation.org/Mussel_Protocols.htm
Species Composition (Biological)	Number of live species (mussels or hosts)	Estimate of biodiversity (species richness) in a defined area.	Many references but Strayer and Smith 2003 is the most extensive reference, but also see Hart et al. 2016 (recent review) and Wisniewski et al. 2013 (complicating factors). https://molluskconservation.org/Mussel_Protocols.htm
Population Structure (Biological)	External age (mussels or hosts) and shell length (SL; mussels)	Counting external rings may underestimate age and overestimate growth rates[28] (Neves and Moyer 1988)	Haag and Warren 2007, Newton et al. 2011, Jones et al. 2018
Density (Biological)	Number of live mussels per m^2 - spatial context for hosts varies by species	See Dunn et al. 2020 for cautionary note about using mean density	Reported as mean density https://molluskconservation.org/Mussel_Protocols.html
Relative Abundance (Biological)	Proportional species' representation in an assemblage (i.e., % of), or proportional age class representation	A biodiversity estimate, or measure of persistence of recruited/stocked population often used with other data for exploring inferences	MacArthur 1957, Payne and Miller 1989, Dunn 2000
Biomass (Biological)	Wet weight (g) mass of sampled live	Can be measured directly in the field or indirectly by	Newton et al. 2011, Ravera et al. 2007.

[28] For cases that require more precise aging for the assessment and/or restoration, consult with mussel SMEs about thin-sectioning combined with microscopic counting of internal growth annuli. The regression relationship between the age at maturity and the von Bertalanffy (1938) growth coefficient (k) can be used to predict breeding age (Haag 2012).

Metric	Example	Comments	References
	individuals (mussels or hosts)	developing length-mass regressions	
Growth (Biological)	Growth rate (separate metric based on size classes [shell length])	Varies by species, type of hosts.	Lane et al. 2021
Survival (Biological)	Direct assessment via PIT tags (mussels) Indirect assessment via catch curves (mussels or hosts)	Mark-recapture requiring unique individual IDs	Kurth et al. 2007, Wisniewksi et al. 2013, Newton et al.2014, 2020 (and many other PIT tag studies) Crabtree and Smith 2009, Newton et al. 2011, Carey et al. 2019
Recruitment (Biological)	Mussels: •# live individuals <5 years old •# live individuals <30 mm SL •# individuals < age of sexual maturity	Little consistency in metrics to assess recruitment. Leads to population growth rate (separate metric based on abundance)	Miller and Payne 1988, Haag and Warren 2007, Newton et al. 2011, Ries et al. 2016, Dunn et al. 2020

Example Goals and Objectives Statements for Freshwater Mussel Restoration Projects

Hypothetical examples of restoration goals in a project where the target is native freshwater mussel populations supported by suitable habitat conditions, as understood by best available science. Note that social and cultural goals – versus ecological -- could also be considered as part of the restoration.

- Restore the native mussel assemblage to approximate baseline or reference conditions.
- Propagate and introduce native mussels into the river with the intent of improving water clarity and supporting aquatic ecosystem function.

Hypothetical examples of ecological objectives for the same project.

- Assemblage of mussel species and age classes, such that mean recruitment is > 5%, similar to reference sites no later than 25 years following reintroduction or augmentation.
- Effective population size (N_e) of 100 containing sufficient genetic variation within river reaches of interest within 25 years following reintroduction or augmentation.

Adaptive Management

Adaptive management in a natural resource management setting (Walters and Holling 1990) employs an iterative approach rooted in flexibility, learning by doing, and responding to challenges based on prior experiences. It is an approach to site management in which relationships between monitoring metrics and the variables influencing them were anticipated during the goal-setting and planning phases. A truly adaptive approach involves exploring alternative ways to meet management objectives, predicting the outcomes of alternatives based on the current understanding of natural systems, implementing one or more of these alternatives, monitoring to learn about the effects of management actions, and then using the results to update knowledge and adjust management actions (Murray and Marmorek 2004). Implementation of adaptive management occurs throughout the duration of restoration as the results of monitoring activities reveal the progress and nature of the recovering resources or ecosystem. Monitoring is thus critical throughout the implementation and recovery phases of the project to allow for “mid-course corrections” or “corrective actions” that fine-tune management activities so that the project is more likely to meet its original goal (Hilderbrand et al. 2005).

According to mussel SMEs, there is a propagation-related publication that mentions adaptive management (Jones et al. 2006) and one under development for the Upper Mississippi River system related to water level drawdowns.[29] As such, NRDAR practitioners do not have a lot of mussel-specific information on adaptive management to use as guidance. As discussed above (Types of Monitoring), monitoring data are reviewed for potential adaptive management. Adaptive management activities should fall within the range of alternatives and nature of potential environmental consequences considered in restoration plans, National Environmental Policy Act documents, and/or project management plans. For example, under an adaptive monitoring scenario, one may attempt to answer whether freshwater mussel populations increased in response to the functional attributes influenced by a series of streambank stabilization projects.

Adaptive management can be a useful tool in realigning project results with restoration goals in an efficient manner. It is particularly important to consider adaptive management early in the planning process, rather than only during later steps, and understand that the relationship between management actions and metric outcomes are not static. With larger, complex restoration projects, it is particularly

[29] Personal communication, Dr. Teresa Newton, USGS, September 20, 2022.

critical to set thresholds that trigger adaptive management actions early in the design process to obtain stakeholder buy-in and to link metrics collected during monitoring to those collected during site evaluation and design. As discussed above (Recommended Monitoring Metrics), the frequency of monitoring can vary but is likely to be a lengthy total timeframe for mussels. The estimated frequency and total number of monitoring events needs to be informed by the potential need for adaptive management.

CLOSING REMARKS

At any phase of a freshwater mussel NRDAR case, it may be necessary to consult with SMEs to evaluate the available relevant science. This includes consultation on information needed to establish baseline of a local population, quantify injury, and identify feasible restoration opportunities, monitoring needs and adaptive management during restoration implementation. Available science may only address certain species or methods that may not be relevant to a case. This document should not be viewed as a constraint on additional scientific and economic study. Where reasonable, it may be appropriate to conduct case-specific assessment studies to provide data and information on which to base the damages. This may include information on baseline and injury, as well as effectiveness of restoration techniques and recovery rates. As previously noted, this document is intended to remain current as a living document. As additional studies are conducted and freshwater mussel NRDAR practice evolves, ORDA intends to periodically update the best practices in this document.

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Appendix A: Supplementary Information on Injury Assessment

Placeholder for future use.

Appendix B: Supplementary Information on Restoration Opportunities, Scaling, and Damages Determination

Summary of Ecological Injury Quantification and Damages Determination Methods

NRDAR practitioners have long used habitat equivalency analysis (HEA) and resource equivalency analysis (REA) for injury quantification and damages determination. These methods equate ecological services or species lost due to contamination (injury) with those gained from restoration activities (also called uplift) relative to baseline. Baseline condition is defined as the condition of the injured resource, including effects from agriculture, urbanization, invasive species, forestry, and climate change, among others, exclusive of changes attributable to the release of hazardous substances or oil spill. That is, "but for" the contamination what are the past, current, and expected future conditions of the resource? Because the effects of time are factored in, these analyses address the "interim loss" of injured resources, which are the losses of natural resources and associated services that occur from the date of the release or spill until recovery (43 CFR Part 11; 15 CFR 990). "Damages" include monetary compensation for restoration or in-kind restoration by the party responsible for the release or spill, as well as monetary compensation for trustees' costs for assessment, restoration planning, and oversight of restoration implementation and monitoring.

HEA focuses on the flow of services (from 0 to 100%) provided by a habitat (Baker et al. 2020, NOAA 2006, Unsworth and Bishop 1994). Service "debits" are the losses and "credits" are the gains relative to baseline habitat conditions, which are adjusted to present-day terms through the use of a 3% discount rate. HEA is usually expressed as discounted service acre-years (DSAYs) to account for changes over time and potential differences between the injury and restoration implementation (NOAA 2006). A DSAY is the present-day services provided by one acre of habitat over 1 year.

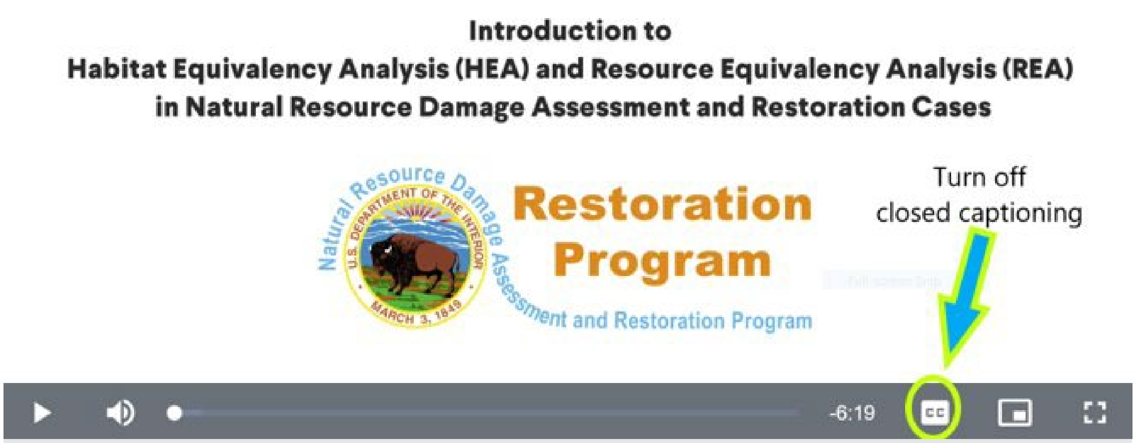
REA uses biological units rather than the habitat (spatial) units of HEA (Baker et al. 2020, Desvousges et al. 2018; Zafonte and Hampton 2007). The biological units of measure for REA typically include individual animals killed, loss of biomass (lethal or sublethal), or reduced density (debit), which is then compared to the expected uplift (credit) produced by restoration. For a kill of individual animals, a life history REA typically employs a stepwise replacement model (Sperduto et al. 2003), which involves basic population modeling including elements of the Leslie matrix (Leslie 1945) and associated life tables (Simpfendorfer 2005). This approach documents how killed individuals should have been alive by age class over time based on survival rates and lifespan, and determines the restoration needed to replace what was lost. The REA can also include forgone reproduction. REA is typically expressed as discounted species-years (DSYs) where a DSY represents one animal over 1 year including its associated services. In application, birds are expressed as DBYs, mussels as DMYs, and fish as DFYs, etc. Extensive time and investment have been made into the development of a mussel REA spreadsheet model. The current iteration is described in Hyde and Jones (2021), which relies on survival rates and recruitment calculations in Jones et al. (2012).

In the case of a biomass REA, losses and gains of resources are typically measured in units of mass per individual per year, and may include a spatial context (e.g., per acre, per square meter). For example, estimates of dead birds can be multiplied by an average mass per bird to calculate the biomass (e.g., discounted kilogram-years) lost (debit), which could then be restored through the provision of more food biomass (discounted kilogram-years per acre restored, called the "relative productivity" of restoration) for the species. The process of restoration "scaling" is used in all of these equivalency methods to ensure the debit equals credit. Scaling would result in acres owed in this example (kilogram-years lost ÷ kilogram-years/acre restored = acres owed). Similarly, losses of vegetation can be calculated in terms of discounted kilogram-years (debit), and then compensated for through restoration projects intended to re-establish vegetation over time (credit). Baker et al. (2022) introduced Habitat-Based Resource Equivalency Methods (HaBREM) as an "augmentation" of existing biomass REA methods. HaBREM can be used to evaluate the sublethal loss of biomass from multiple species (debit) and determine whether, when, and how a single type of restoration can produce sufficient biomass to offset the losses (credit).

Where possible, a REA using the net change in density for the debit and credit can be ideal. NRDAR practitioners would need to know the baseline density of species per habitat type(s) for comparison to the current and projected annual density of species per habitat type(s) injured by a contaminant. Density is typically expressed as an average discounted number of animals per spatial unit (e.g., DBYs per acre for birds, DMYs per square meter for mussels, DFYs per river-mile for fish). The discounted annual density is applied to the total injured area to estimate the REA debit. Crediting is calculated based on the improvement in discounted annual density over time from restoration activities. The annual density already reflects the local population dynamics, so additional life history information (survival rates, lifespan, reproduction) is not needed.

In addition to the equivalency analysis methods, NRDAR practitioners can choose to directly restore to baseline. This could involve 1:1 restoration (e.g., restore the injured site to baseline through replanting) or replacement (e.g., replace the loss of 100 mussels with 100 propagated mussels). A multiplier could also be used (e.g., use the survival rate for reintroduced mussels to inform the number of mussels needed to result in 100 mussels replaced). Direct replacement does not include interim losses, i.e., there is no consideration of the effects of time or use of discounting.

A visual overview of HEA and REA is available at: https://www.doi.gov/restoration/hearea. Users should turn off the closed captioning in the player, as shown below. Accurate closed captioning is provided in the video.



NRDAR practitioners are reminded to work closely with their case economists to better understand these methods.

Table B-1. Life stage specific restoration opportunities and potential endpoints[31]

Endpoint	**Life stage**		
	Glochidia	Juvenile	Adult
Mortality (mussels and hosts)	• Propagation and reintroduction (missing age classes)	• Propagation and reintroduction • Mussel habitat creation/ enhancement/avoided loss	• Propagation and reintroduction • Mussel habitat creation/ enhancement/avoided loss
Reproduction	Not applicable	Not applicable	• Propagation and reintroduction • Mussel habitat creation/ enhancement/avoided loss
Biomass	Not applicable	• Water quality/quantity • Mussel habitat creation/ enhancement/avoided loss • Buffer habitat	• Water quality/quantity • Mussel habitat creation/ enhancement/avoided loss • Buffer habitat
Growth	Not applicable	See biomass endpoint	See biomass endpoint
Other sublethal (behavior and physiology)	Not applicable	• Mussel habitat creation/ enhancement/avoided loss	• Mussel habitat creation/ enhancement/avoided loss

Table B-2. Damages Determination Methods Given Life Stage and Affected Endpoints in Injury Determination and Quantification

Endpoint	**Life stage**		
	Glochidia	Juvenile	Adult
Mortality	Missing age classes: • Direct replacement • Life history/density REA	• Direct replacement • Life history/density REA • HEA	• Direct replacement • Life history/density REA • HEA
Reproduction	Not applicable	Not applicable	• Direct replacement • Life history/density REA
Biomass	Not applicable	• Direct replacement • Biomass REA (HaBREM) • HEA	• Direct replacement • Biomass REA • HEA
Growth	Not applicable	• HEA • Translated to biomass; see biomass endpoint	• HEA • Translated to biomass; see biomass endpoint
Other sublethal (behavior and physiology)	Not applicable	• HEA	• HEA

[31] All of these restoration options can also be relevant to human/cultural use losses and could include land acquisition and infrastructure. Tribes may have additional cultural needs that should be addressed separately.

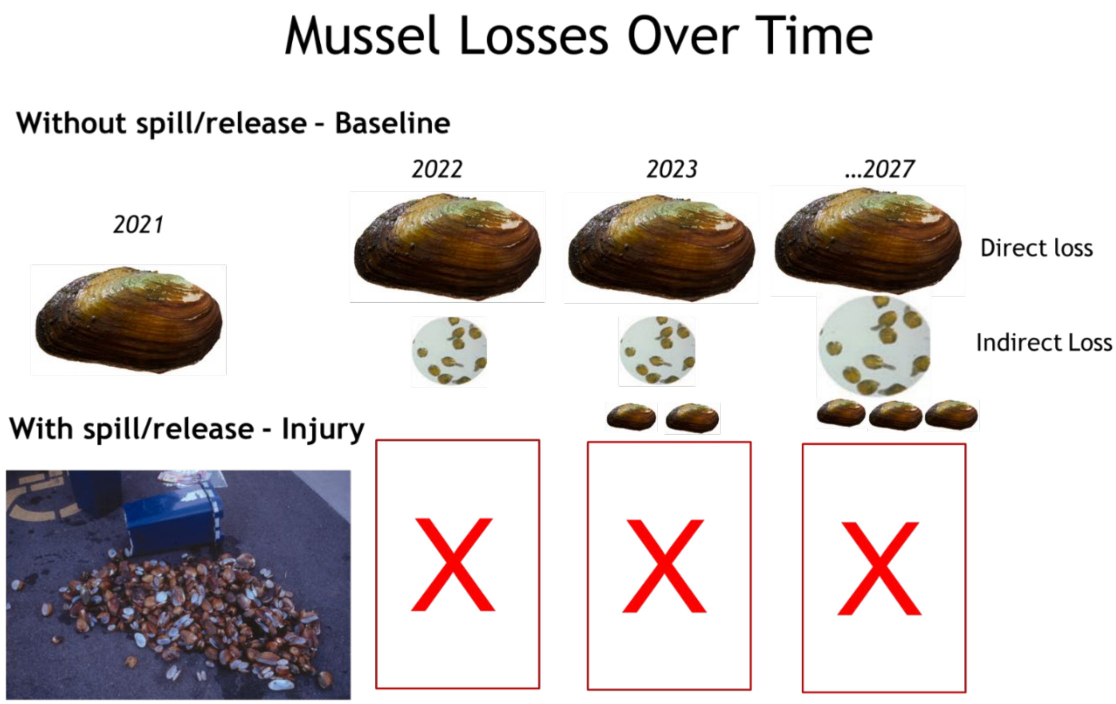


Figure B-1. Simplified illustration of direct (adult) and indirect (forgone reproduction) mussel losses over time for use in REA

Figure B-2. Illustration of foundational concept of equivalency analysis using the metric of DMYs

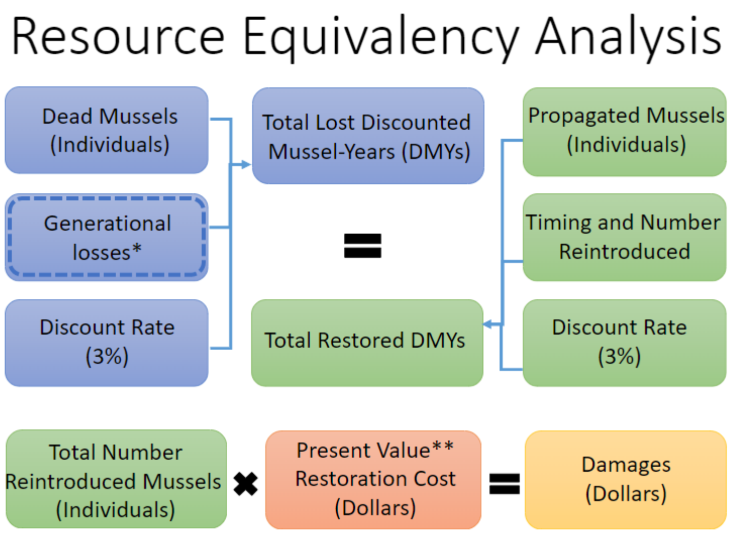


Figure B-3. Injury Quantification, Restoration Scaling, and Damages Determination for Freshwater Mussels Using Resource Equivalency Analysis (REA)

*Generational losses should be evaluated; consult with your case solicitor and case economist on whether it is beneficial to include them.
**Restoration cost estimation involves consideration of the future flows of costs, including inflation and potential interest from Interior's Restoration Fund (Fund Manager collects, invests, and disburses case settlement funds), all of which are converted to present value. This process is conceptually different from the 3% discount rate applied to ecological resources in equivalency analyses.

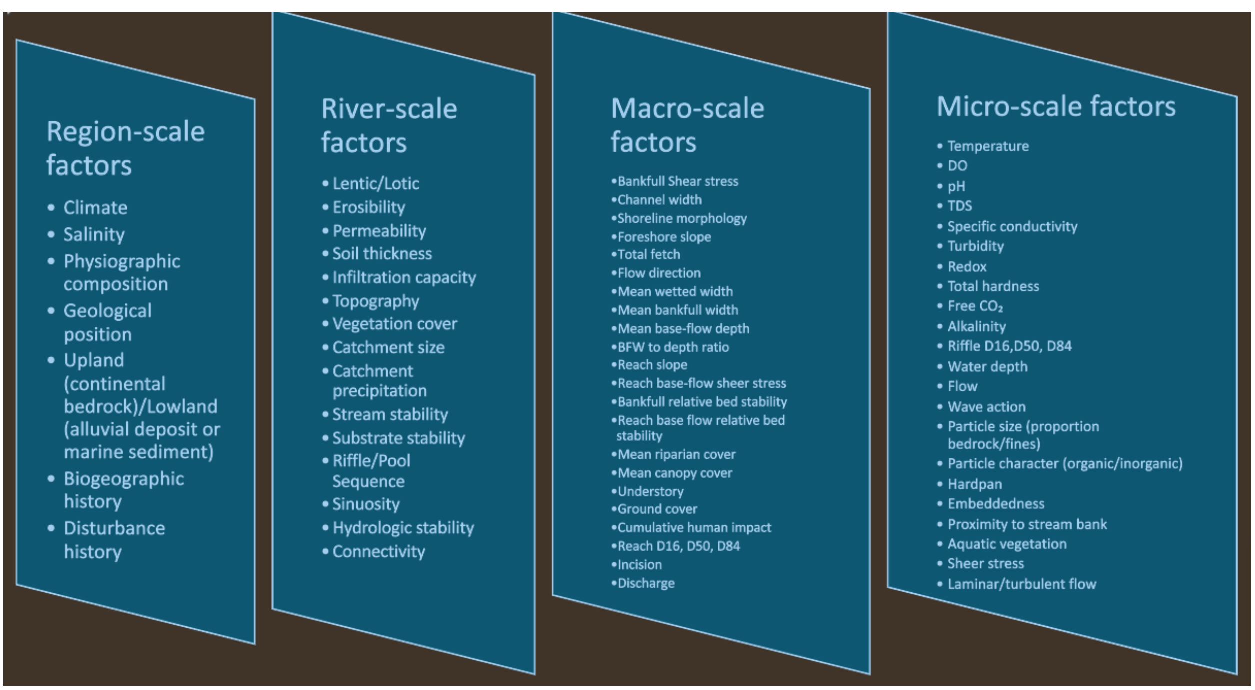


Figure B-4. Optimal habitat variables for consideration in evaluating mussel habitat (Strayer 2008)

Appendix C: Mussel Propagation Facility Locations Across North America

Facility	Location	Entity
Alabama Aquatic Biodiversity Center	Alabama	Alabama Department of Conservation Natural Resources
Greers Ferry National Fish Hatchery	Arkansas	U.S. Fish and Wildlife Service
Norfork National Fish Hatchery	Arkansas	U.S. Fish and Wildlife Service
Welaka National Fish Hatchery	Florida	U.S. Fish and Wildlife Service
Warm Springs National Fish Hatchery	Georgia	U.S. Fish and Wildlife Service
Urban Stream Research Center	Illinois	Forest Preserve District of DuPage County
Kansas Aquatic Biodiversity Center	Kansas	Kansas Department of Wildlife and Parks
Center for Mollusk Conservation	Kentucky	Kentucky Department of Fish and Wildlife
Wolf Creek National Fish Hatchery	Kentucky	U.S. Fish and Wildlife Service
Natchitoches National Fish Hatchery	Louisiana	U.S. Fish and Wildlife Service
North Attleboro National Fish Hatchery	Massachusetts	U.S. Fish and Wildlife Service
Richard Cronin Aquatic Resource Center	Massachusetts	U.S. Fish and Wildlife Service
Institute for Great Lakes Research	Michigan	Central Michigan University
Center for Aquatic Mollusk Programs	Minnesota	Minnesota Department of Natural Resources
Missouri State University	Missouri	Missouri State University
Neosho National Fish Hatchery	Missouri	U.S. Fish and Wildlife Service
North Platte State Fish Hatchery	Nebraska	NGPC
Aquatic Epidemiology and Conservation Laboratory	North Carolina	NC State University
Marion Conservation Aquaculture Center	North Carolina	North Carolina Wildlife Resources Commission
Freshwater Mussel Conservation and Research Center	Ohio	Columbus Zoo and Aquarium
Peoria Tribe of Indians Aquatic Facility	Oklahoma	Peoria Tribe of Indians
Bears Bluff National Fish Hatchery	South Carolina	U.S. Fish and Wildlife Service
Orangeburg National Fish Hatchery	South Carolina	U.S. Fish and Wildlife Service
Cumberland River Aquatics Center	Tennessee	Tennessee Wildlife Resources Agency
Dale Hollow National Fish Hatchery	Tennessee	U.S. Fish and Wildlife Service
Inks Dam National Fish Hatchery	Texas	U.S. Fish and Wildlife Service
San Marcos Aquatic Resource Center	Texas	U.S. Fish and Wildlife Service
Uvalde National Fish Hatchery	Texas	U.S. Fish and Wildlife Service
Aquatic Wildlife Conservation Center	Virginia	Virginia Department of Wildlife Resources
Freshwater Mollusk Conservation Center	Virginia	Virginia Tech
Harrison Lake National Fish Hatchery	Virginia	U.S. Fish and Wildlife Service
Confederated Tribes of the Umatilla Indian Reservation/Walla Walla Community College Aquatic Propagation Laboratory	Washington	Confederated Tribes of the Umatilla Indian Reservation
White Sulphur Springs National Fish Hatchery	West Virginia	U.S. Fish and Wildlife Service
Genoa National Fish Hatchery	Wisconsin	U.S. Fish and Wildlife Service
Normandale Fish Culture Station	Ontario, Canada	Ontario Ministry of Natural Resources
White Lake Fish Culture Station	Ontario, Canada	Ontario Ministry of Natural Resources

Appendix D: Supplementary Information on Mussel Restoration

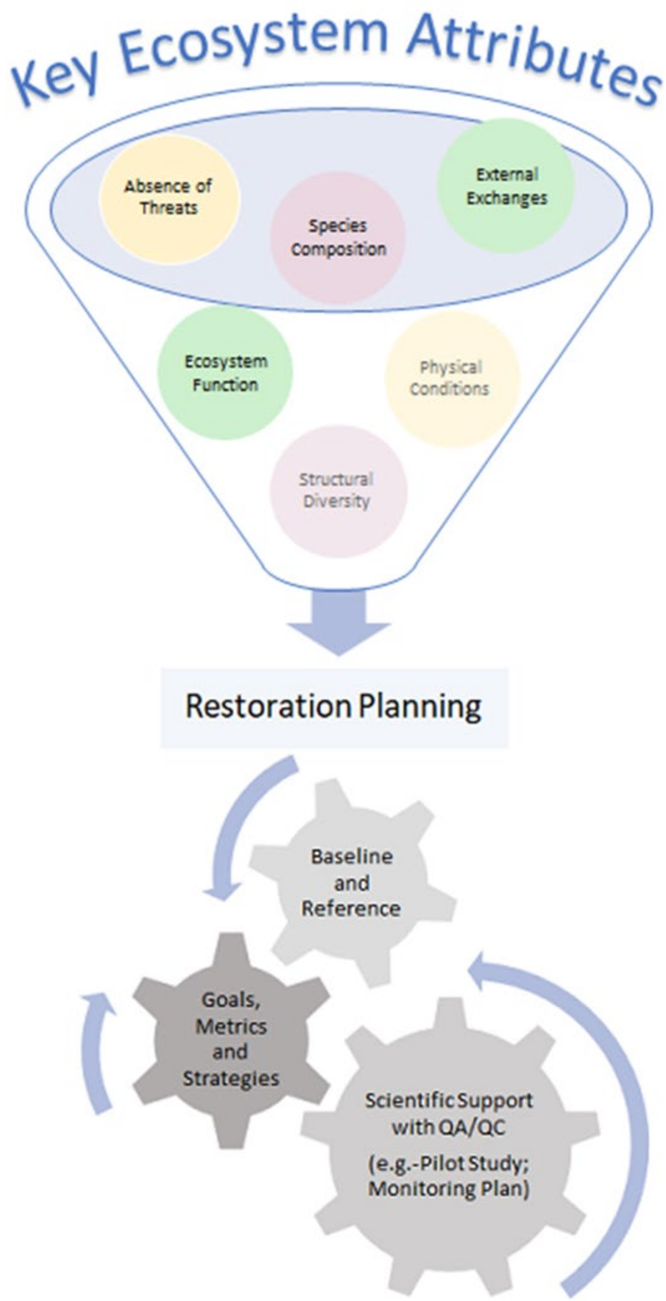


Figure D-1. Restoration planning with ecosystem attribute inputs

Ecosystem Services from Mussels

Ecosystem services provided by freshwater mussels can be classified using the standard Millennium Ecosystem Assessment[32] categories: provisioning, regulating, supporting, and cultural (Vaughn and Hoellein 2018).

- **Provisioning and Cultural Services** include the historic use of mussel shells for buttons, and the recent use of shells for the pearl jewelry industry (Strayer 2017). As mentioned in the injury assessment section, Tribes have long considered freshwater mussels as a valuable cultural resource, including for food, tools, jewelry, regalia, and spiritual purposes (Brim Box et al. 2006, Haag 2012). Tribal SMEs have indicated the individual size of mussels can be very important. See Quaempts et al. (2018) for a First Foods example from the Confederated Tribes of the Umatilla Indian Reservation that includes mussels.
- **Regulating and Supporting Services** include direct and indirect effects on aquatic food webs, nutrient cycling and storage, habitat creation and modification, nutrient and contaminant sequestration, and biofiltration (Vaughn and Hoellein 2018). Mussel beds support other organisms like benthic algae, macroinvertebrates, and fish (Vaughn 2010). Live mussels are an important food resource for fishes, mammals, and birds, and dead shells are a source of calcium as well as habitat for aquatic organisms (Vaughn 2010). Biodeposits from mussel feeding provide food for bottom animals and fertilizer for plants (Vaughn et al. 2008, Strayer 2014, Atkinson and Vaughn 2015). Mussel wastes allow for nitrification/denitrification processes by the benthic microbial community (Atkinson et al. 2018, Hoellein et al. 2017, Nickerson et al. 2019). Mussels may also enhance habitat conditions by stabilizing and aerating sediments (Zimmerman and de Szalay 2007, Allen and Vaughn 2011).
    - Freshwater mussels filter seston[33] and associated particles, including contaminants, from water. Because mussels need to filter large quantities of water to meet their nutritional requirements (Bayne and Newell 1983), clearance rates (i.e., the volume of water cleared of particles) often exceed one liter per hour per gram of dry mussel tissue, or 0.024 cubic meters per square meter per day ($m^3/g/d$) (Kreeger et al. 2018). Clearance rates vary by body size. Example filtration rates are in HRNRT (2020b) and Mistry and Ackerman (2018).
    - Suspended microscopic particles may also be filtered by freshwater mussels, including nitrogen and phosphorus, total suspended solids (TSS), pathogens and contaminants. Numerous case studies have shown that bivalve filter-feeding can promote water clarity if the population biomass is high relative to water volume and hydrological residence time (see, e.g., Cerco and Noel 2010, Thompson 2005, Alpine and Cloern 1992).

Mussels as a Potential Best Management Practice (BMP)

The biofiltration benefits of a mussel population to water quality can be estimated from the volume of water filtered by the mussels, the concentration and composition of particles in the water (i.e., TSS or contaminant loads), and physical properties that govern access to the particles by mussels (e.g., hydrodynamic residence time, depth, circulation). Other factors such as temperature, species, size, and physiological condition can also influence biofiltration rate. Recognizing there are potential confounding variables, mussel SMEs assert the biomass of the total mussel assemblage (e.g., kilograms of dry tissue mass per hectare) is a useful proxy for estimating the filtration related ecosystem services of mussel

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[32] https://www.millenniumassessment.org/en/index.html

[33] Seston is living and nonliving microparticulate matter that is suspended in the water column (see, e.g., Kreeger and Newell 2001).

assemblages *in situ* but this calculation does not capture the entirety of ecosystem services provided by freshwater mussels. Population biomass can be estimated by integrating quantitative density data with species- and size-specific biomass data. Specifically, mussel surveys provide measures of biomass, which can be used to estimate filtration rates (see Newton et al. 2011). With estimates of TSS (e.g., from state water quality reports), it is a desktop exercise to estimate TSS removed that should be reported as a static result.

For denitrification, the Scientific and Technical Advisory Committee (STAC), which provides scientific and technical guidance to the Chesapeake Bay Program (CBP), held a workshop with mussel SMEs and prepared a recent illustration on the role of mussels and nitrogen (N) in the Chesapeake Bay (STAC 2021). They shared:

> Our estimates suggest current mussel density provide a net benefit of mussel denitrification of 0.001% to 1.2% of current loads…one acre of existing mussel bed at the highest densities we have been able to document in the watershed, (25 individuals m-2), would theoretically offset approximately 75 lbs. of N which represents loading from 5-10 acres of agricultural nitrogen loads [from] agricultural or developed land use…To put these number[s] in perspective, 1 acre of forested stream exclusion buffers would offset roughly 100 lbs. of Nitrogen. Likewise, 1 acre of cover crops would address approximately 3 lbs. of nitrogen annually (STAC 2021: 24-5).

For NRDAR cases that are considering riparian buffers and BMPs like fencing to take up and reduce the run-off of nitrogen (N), phosphorous, and TSS, it may be feasible to also consider mussel restoration as part of the scaling exercise. NRDAR practitioners should also be clear that N—as ammonia—is extremely lethal to mussels. So, forms of N and the abiotic and biotic conditions at a site should not be ignored.

See Harrison Lake National Fish Hatchery's YouTube video on mussel services, including water filtration and food provisioning, as well as the importance of fish hosts. https://www.youtube.com/watch?v=gv1kCUOtY48

See the Freshwater Mollusk Conservation Center at Virginia Tech's YouTube videos on mussels services and Clinch River, Virginia, NRDAR mussel reintroduction. https://www.youtube.com/watch?v=vrRglj3bPRg; https://www.youtube.com/watch?v=SKjVdh1cAY4

Precautions to Prevent the Spread of Invasive Species

The Department has extensive guidance on invasive species, including definitions,[34] Federal guidance,[35] and Departmental Strategic Plan and Guidance,[36] as well as bureau responsibilities.[37]

Specific protocols for preventing the spread of zebra mussels can be found in Gatenby et al. (1998) and Cope et al. (2003). Invasive species should be considered during the restoration planning process. Cope et al. (2003) explores relocation of native mussels to "various types of refugia for their protection and conservation against invasive zebra mussels" (p. 27). Relocations would be considered an avoided loss type of project in NRDAR cases.

Example of Post-Settlement Mussel Restoration Strategy Document

This is a placeholder for text to be added/linked to by the South River NRDAR Case Manager. The final version is intended to provide more detail on the background/injury analysis/restoration goals than what was in the Restoration Plan/Environmental Assessment (RP/EA) and is intended to be a "living" document that keeps track of restoration sites, etc. For more immediate information needs, please contact Anne Condon, USFWS, Virginia Field Office (anne_condon@fws.gov).

[34] https://www.doi.gov/sites/doi.gov/files/uploads/isac_definitions_white_paper_rev.pdf
[35] https://www.doi.gov/invasivespecies/guidance-documents
[36] https://www.doi.gov/ppa/office-of-policy-analysis-invasive-species-coordination
[37] https://www.doi.gov/ppa/bureau-and-office-invasive-species-overview