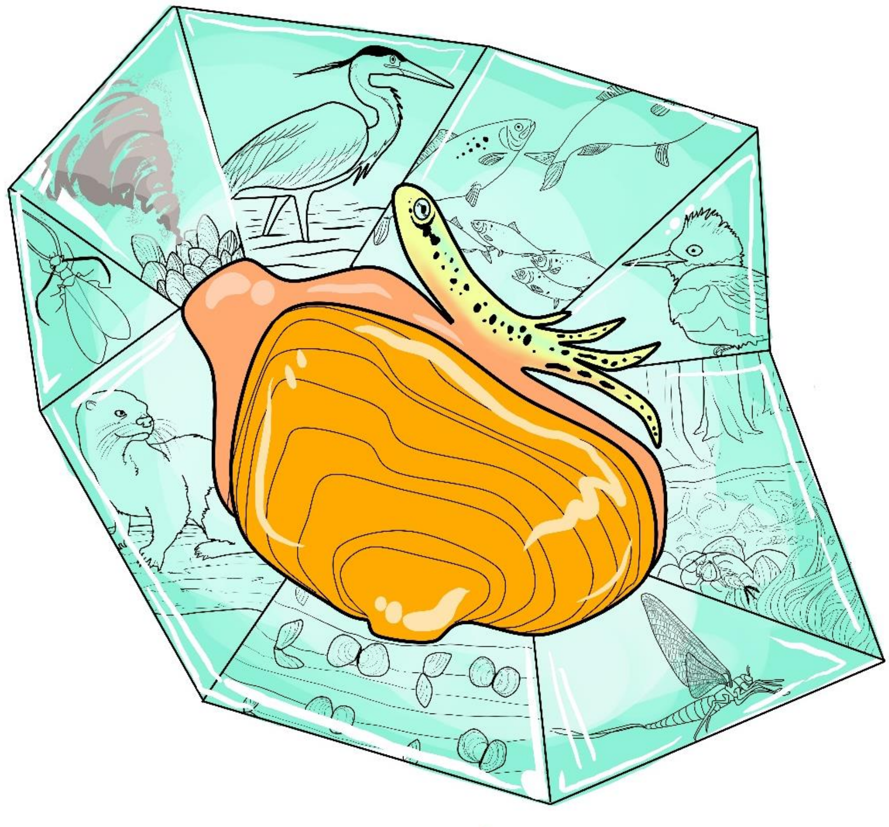
Incorporating Freshwater Mussels into the Chesapeake Bay Restoration Efforts



STAC Workshop Report

March 5-6, 2020

Chesapeake Bay Foundation Philip Merrill Center

Annapolis, MD

STAC Publication 21-004

About the Scientific and Technical Advisory Committee
The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the watershed. For additional information about STAC, please visit the STAC website at www.chesapeake.org/stac.

Publication Date: July 28, 2021

Publication Number: 21-004

Suggested Citation: Wood, J., P. Bukaveckas, H. Galbraith, M. Gattis, M. Gray, T. Ihde, D. Kreeger, R. Mair, S. McLaughlin, S. Hahn, A. Harvey. 2021. Incorporating Freshwater Mussels into the Chesapeake Bay Restoration Effort. STAC Publication Number 21-004, Edgewater, MD. 39 pages.

Cover graphic: TOC by Rebecca Culp, Chesapeake Bay Foundation

STAC Administrative Support Provided by:
Chesapeake Research Consortium, Inc.
645 Contees Wharf Road
Edgewater, MD 21037
Telephone: 410-798-1283
Fax: 410-798-0816
http://www.chesapeake.org

Workshop Steering Committee
Joseph Wood (Chair), Chesapeake Bay Foundation
Paul Bukaveckas, Virginia Commonwealth University
Heather Galbraith, Pennsylvania Fish and Boat Commission
Mary Gattis, Private Consultant, Mary Gattis LLC
Matthew Gray, University of Maryland Center for Environmental Science
Danielle Kreeger, Partnership for the Delaware Estuary
Rachel Mair, US Fishing and Wildlife Service
Shawn McLaughlin, National Oceanic and Atmospheric Administration
Simeon Hahn, National Oceanic and Atmospheric Administration
Tom Ihde*, Morgan State University

STAC Staff:
Annabelle Harvey, Chesapeake Research Consortium, Edgewater, Maryland.
Meg Cole, Chesapeake Research Consortium, Edgewater, Maryland.

**STAC member*

Acknowledgements

The steering committee is grateful to the efforts of several workshop participants which helped provide pieces of this report. Specifically, Carla Atkinson, Jeff Cornwell, Lisa Kellogg, Denis Newbold, and Dave Strayer were instrumental in providing information and guidance on denitrification extrapolations.

Contents

Executive Summary

Freshwater mussels were chosen as a focus for this workshop to consider ecosystem services, document biodiversity, outline intersections with Chesapeake Bay issues and to explore their potential to engage partners. The workshop brought diverse expertise together from across the watershed including mussel biologists, nutrient dynamics experts and water quality managers to provide recommendations which are summarized in this report.

Freshwater mussels have significant ecological value and directly benefit several Bay restoration goals. Yet these animals, which are highly threatened, have received very limited attention in the Chesapeake Bay Restoration efforts. The goals of the Chesapeake Bay Agreement include all shellfish; however, partnership logic and action plans have not yet included any specific efforts related to freshwater mussels. As a result, restoration funds being awarded by partner funding organizations (i.e. National Fish and Wildlife Foundation (NFWF)) are not targeted towards protecting these valuable and highly threatened populations.

Documenting existing mussel resources is an important goal. The Chesapeake Bay Watershed is home to more than 25 species of native freshwater mussels, many of which are threatened or endangered. State and federal partners have assembled databases of mussel distributions and there have been multiple species distribution models published spanning the Bay Watershed but many of the existing datasets are not in a common form, and as such assessing the Chesapeake Bay mussel resource is challenging. Improving standardization of future surveys would improve new efforts to assess the resource.

Mussels provide ecosystem services which benefit water and habitat quality. Recent peer-reviewed literature indicates that mussels enhance denitrification in freshwaters, which is directly relevant to nitrogen loads. Our review suggests mussel populations, which have widespread habitat ranges across freshwater, have the capacity to play a role in nitrogen delivery to the Chesapeake Bay. Phosphorus and sediment may also be sequestered although because they are not removed from the river system their ultimate delivery to the bay is still probable. Widespread population declines have substantively reduced these services, but ongoing and future restoration efforts could enhance these benefits. Important knowledge gaps remain including an improved documentation of current populations (i.e. enhanced surveys) and more localized estimates of these ecosystem services. The Chesapeake Bay Program partnership (henceforth, the partnership) should support research to help more precisely quantify these services and work to incorporate these results into the management framework via a BMP expert panel and other modeling pursuits.

Threats to freshwater mussel populations regularly intersect with water management issues, yet, guidance for optimizing both goals is absent. Specifically, disruptions in the flow have significant impacts to mussels and can be exacerbated by various pressures (e.g. development), and in some cases water management efforts. The partnership should enhance research efforts surrounding threats to mussel communities and pursue guidance on BMPs that will help resolve conflicts and encourage optimization for both goals. This effort would avoid impacts to mussels and help maintain ecosystem services.

Freshwater mussels offer a potential mascot for Chesapeake Bay initiatives due to a distribution across freshwater, biodiversity, complex life-histories, and beneficial ecosystem services for local waters. Enhancing focus on freshwater mussels will help engage communities in restoration efforts in places where other iconic species are absent. We encourage the partnership to utilize mussels to serve as a communication tool to promote the needs and benefits of clean water and environmental stewardship.

In conclusion, freshwater mussels represent a Chesapeake Bay resource that provides a rich variety of benefits and opportunities that can enhance the Partnership's restoration efforts. We urge the partnership to incorporate these benefits through the following consensus recommendations:

1. Consideration of how to protect and restore freshwater mussels should be included within the Bay program's work-planning efforts. Specifically, an important first step is that mussels should be included as a priority target species group for NFWF funding streams. Further, the Fish Habitat Action Team, Habitat Goal Implementation Team (GIT), and the related workgroups should explicitly outline objectives to improve protection and restoration of mussel populations and their habitats
2. The partnership should work with the Fostering Chesapeake Stewardship GIT to utilize freshwater mussels to engage communities in Chesapeake Bay restoration efforts in freshwater portions of the watershed. Specific steps can be taken in connection with the partnering with the Chesapeake Monitoring Cooperative to provide guidance on how mussels could be incorporated in citizen monitoring efforts, incorporation into Meaningful Watershed Education Experiences (MWEEs) and Bay Backpack environmental literacy efforts, enhanced communications on the subject of mussels, and inclusion as a 'co-benefit' in CAST modeling efforts.
3. The Chesapeake Bay Monitoring Team should support partner agencies in mussel survey efforts and include mussels as a biological characteristic in their regular monitoring program. Specific attention should be given to documenting high density mussel beds and mapping suitable habitat and assessing anthropogenic stressors. Further, the Monitoring Team should support efforts to aggregate and summarize this information across the watershed.
4. The Strategic Science and Research Framework should be revised to include pertinent 'science needs' that are focused on the protection and restoration of freshwater mussel populations across the watershed. Specifically, science needs should be added to enhance our understanding of freshwater mussel habitat suitability (Supportive of Habitat GIT); improve our efforts to survey and track mussel populations (Supportive of Fish Habitat Action team) and evaluate nutrient benefits (e.g. denitrification) associated with Bay watershed freshwater mussel populations (Supportive of the water quality GIT) . These relevant cohorts should include the science needs for incorporation into the SSRF for review by STAR and the Management Board, as required by the Strategic Review System. Ultimately, the partnership should pursue these science needs and use results to inform a BMP expert panel on the subject of freshwater mussels.

5. The Water Quality GIT and Sustainable Fisheries GIT should support efforts to evaluate conflicts and opportunities between nutrient mitigation and mussel restoration efforts and provide guidance to mangers on how to navigate. Specific attention is needed focused upon potential impacts of stream restoration on mussel populations and intersections between mussel-based ammonia criteria and nitrogen delivery to the bay.

Additional details regarding the recommendations from this workshop are in the Summary of Workshop Recommendations Section of the report.

Introduction

Freshwater mussels are a diverse group of organisms that are threatened by numerous impacts to water resources. These organisms, which are linked by their life-history to fish, provide ecosystem services including improving water quality through their filtration and can enhance denitrification rates. Further, mussels occur broadly across freshwater habitats of the Chesapeake Bay watershed where other iconic species are not present. The 2014 Chesapeake Bay Watershed Agreement includes goals to improve habitat and protection for all shellfish. While significant restoration efforts have focused on oysters, few initiatives have focused on other bivalves. Mussel propagation techniques have vastly improved in recent decades which present new opportunities for restoration efforts.

A STAC workshop was held to bring mussel experts together with water quality managers to synthesize current knowledge of mussel populations, including potential for ecosystem services, most prominent threats, potential for restoration and opportunities to engage citizens. The purpose of the workshop was to identify the most effective ways the Chesapeake Bay partnership could incorporate freshwater mussels into their planning and restoration efforts. The specific objectives of the workshop were as follows:

(1) Present current knowledge of freshwater mussel distributions, ecosystem services, threats and potential for restoration.
(2) Summarize nutrient removal and sequestration by freshwater mussel populations, and associated knowledge gaps.
(3) Estimate potential impact of freshwater mussels upon nutrient delivery to the Chesapeake Bay based on latest science.
(4) Identify the most pressing threats and research needs that will enable integrated management approaches for mussels.
(5) Identify opportunities to enhance citizen engagement and education in Chesapeake Bay initiatives through freshwater mussels.

Section 1. Expanding our Knowledge of Freshwater Mussels in the Chesapeake Bay Watershed

The Chesapeake Bay watershed spans 64,000 square miles across six states and the District of Columbia and encompasses an array of environmental conditions. The hydrography for this region represents diverse bivalve habitat extending from the headwaters to the confluence with the Atlantic Ocean. In freshwater reaches of the watershed, mussels from the family Unionidae (hereafter "freshwater mussels") were historically widespread even though abundance was likely variable. Freshwater mussels are known to provide important functions to aquatic ecosystems and valuable ecosystem services to humans by improving water quality through filtration, in addition to playing a role in the food web. Over the past two hundred years, mussels have experienced dramatic declines and have been extirpated in many portions of the Chesapeake Bay Watershed due to significant and emerging anthropogenic stressors including dams, deforestation, urbanization and degraded water quality. Despite these and other anthropogenic pressures, substantial freshwater mussel populations remain in the Chesapeake Bay watershed today. Here we summarize how freshwater mussel populations in the bay might be protected and restored to align with existing Chesapeake Bay goals and provide recommendations for improving our knowledge of this important natural resource.

Through this workshop, participants identified more than 25 species of freshwater mussels (Unionidae and Margaritiferidae) that exist within the Chesapeake Bay basin (Table 1.1). Workshop attendees identified 3 federal and 10 state endangered listings. The Susquehanna, Potomac, Rappahannock, York and James watersheds support 18, 21, 18, 18 and 17 species respectively. Among the watershed states and the District, each jurisdiction has at least 11 and up to 23 species of freshwater mussels that live within the watershed. Freshwater mussels represent a considerable proportion of shellfish biodiversity across the watershed.

Incorporating Mussels into CBP Outcomes

Protection of freshwater mussels is encompassed by several goals and outcomes of the 2014 Chesapeake Bay Watershed Agreement, although they have not been explicitly cited. Specifically, mussels fall into the category of protection described by the Agreement's Sustainable fisheries goal and the Vital Habitats goal. Mussels are also included in the Sustainable Fisheries' Fish Habitat Outcome. Shellfish are also mentioned in the Fish Habitat Management Strategy for this outcome. Despite these inclusions, shellfish have yet to be addressed in the associated 2-year work plan developed by the cross-GIT Fish Habitat Action Team or specifically cited across workplans. A specific consequence of this omission, is that National Fish and Wildlife Foundation (NFWF) which looks to the partnership's workplans in order to establish priorities, does not currently prioritize mussel restoration

Mussels are encompassed by the Chesapeake Bay Agreement, and as such should be specifically included within the relevant workplans and funding efforts. Mussels represents an important component of the watershed's overall shellfish populations, and one of the most sensitive and biodiverse classes of wildlife. Further, mussel habitat exists broadly across freshwater. As such, mussels deserve specific attention from the partnership. Any future revision of the goals would benefit by clearly identifying protection of mussels and establishing relevant goals. While not

Mussels in the Chesapeake Bay Agreement

Sustainable Fisheries Goal: "Protect, restore and enhance finfish, **shellfish** and other living resources, their habitats and ecological relationships to sustain all fisheries and provide for a balanced ecosystem in the watershed and Bay."

Fish Habitat Outcome: "Continually improve effectiveness of fish habitat conservation and restoration efforts by identifying and characterizing critical spawning, nursery and forage areas within the Bay and tributaries for important fish and shellfish, and use existing and new tools to integrate information and conduct assessments to inform restoration and conservation efforts."

Vital Habitats Goal: "Restore, enhance and protect a network of land and water habitats to support fish and wildlife, and to afford other public benefits, including water quality, recreational uses and scenic value across the watershed."

Adopted principals from the Fish Habitat Outcome Management Strategy, 2015–2025, v.2 "Reverse declines, where possible, in the quality and quantity of tidal and freshwater habitats to improve the overall quality of fish and shellfish habitat."

the focus of our workshop, participants also agreed estuarine species, such as ribbed mussels are included and should be specifically called out.

Specific action related to shellfish, both estuarine and freshwater species, should be articulated in the corresponding 2-year work plan. Several recommendations, in this chapter and throughout this report, may serve as potential additions to the work plan. Addressing mussels specifically would encourage funding for the protection and restoration of mussels as originally provided for by the Watershed Agreement through the CBP GIT funding program. Further, this would encourage funding through other programs that look to consider CBP goals, such as the NFWF. We urge the partnership to address mussel considerations in the next Fish Habitat Outcome 2-year Workplan. Specifically, shellfish are mentioned in the outcomes for the Fish Habitat Action Team, a workgroup for of the Sustainable Fisheries Goal Implementation Team (GIT).

Collecting and organizing informational resources across the watershed

Workshop participants identified a rich source of historical field surveys of mussel populations and inventories of mussel populations that have been primarily collected by state wildlife agencies and federal initiatives (Table 1.2). Important knowledge gaps remain in our understanding of the distribution and abundance of freshwater mussel populations, due to the difficulty in aggregating and summarizing data for these resources across the watershed and due to minimal funding initiatives for mussel population monitoring.

One challenge to integrating distribution and abundance information is that datasets are not standardized, and often include different attributes. For example, some data sets only include threatened species, negative data are not always recorded, abundance and surveys for juveniles, which can be time-consuming to collect, is only available in limited situations, and survey methods differ. Data sharing sensitivities also pose a challenge, particularly with regard to policies concerning location information of threatened and endangered species, which prohibit complete disclosure of these datasets. Still, the workshop participants agreed there is significant value in reviewing and aggregating these data sets to help guide and design surveys that would provide needed information. For example, it may be possible to compile and share metadata from the different databases.

Such a resource would allow for spatial hypothesis testing of important research questions focused upon threats to mussel habitat. For instance, it is well documented that climate change and increases in impervious surface, are leading to changes in the magnitude, duration and timing of flows, and such impacts represent a threat to aquatic life (Poff and Zimmerman 2009, Acreman et al. 2014, Yarnell et al. 2020). An inventory of mussel surveys would allow researchers to pose questions about the impacts of flow to freshwater mussel habitat (or similar questions) and target new surveys to explicitly test hypotheses.

Developing a thorough understanding of existing freshwater mussel abundance, distribution and population demographics is a critical first step to protecting and restoring the resource. Specifically, it is important to determine whether populations are increasing, stable or declining, as well as the rate of population changes. Identifying high density mussel sites, the deserve protection, also represents an important outcome of surveys. Life tables that delineate age structure of populations would also be helpful. This information has important implications for improving our understanding of mussel habitat, assessing ecosystem services provided by mussels, as identifying areas of sensitivity, understanding interconnected fisheries resources, and assessing damages in the case of environmental impact. A comprehensive resource that outlines freshwater mussel inventories across the Chesapeake Bay Watershed is currently unavailable. Workshop participants agreed that the partnership could help address this important knowledge gap.

Specifically, the Partnership should explore options for compiling a comprehensive set of current and historic mussel distribution data In order to allow broad access to a publicly available database, this information needs to be aggregated at a level that will protect privacy. Users could then evaluate trends in mussel populations over time and space, and could compare mussel distribution data with water quality data as well as information about barriers (does this refer to barriers affecting dispersal?), past and present habitat destruction or instability, etc. As the available data on historical mussel distribution data may not be sufficient to meet these goals with any degree of rigor, the partnership should work to guide, design and fund new surveys that would provide additional information as needed.

Such an effort could be moved forward through the Chesapeake Bay Habitat GIT, which could work to identify funding and a partner to compile the data, identify gaps, and fund small, directed surveys/monitoring. Utilizing an existing data platform would be optimal and avoid redundancy. This effort could follow a similar model to the fish passage prioritization tool that was developed through the fish passage workgroup of the Habitat GIT. (https://maps.freshwaternetwork.org/chesapeake/). Ultimately, the partnership will need to secure funds for good quantitative surveys over broad scales to improve our understanding of mussel distributions.

The Scientific, Technical Assessment and Reporting team (STAR) should support efforts to better understand current conditions related to mussel extent. Specifically, STAR could help manage survey data, analyze trends, explain conditions and predict responses to change. Further, surveys could incorporate hypothesis testing. States could support this effort by including mussel surveys and restoration efforts in their funding priorities and providing data to the Partnership, but state appropriators will need to invest in these programs.

The proposed georeferenced spatial database will improve the partnership's capacity to assess mussel trends, identify "hotspots" where mussel protection is most needed, and evaluate mussel restoration efforts. This tool should be aligned with other robust datasets such as fish passage and habitat, that the Partnership has established. Further, such a tool would allow the Partnership to evaluate the scale of ecosystem services for past, current and future populations, and improve records for assessing damages in the event of a significant disturbance.

Conclusions

Mussel diversity represents a rich source of biodiversity within The Chesapeake Bay Watershed and substantive efforts have been made to document mussel distributions. Still, there are significant gaps in our understanding of mussel distributions and abundances. Workshop participants agreed that spatially and temporally aggregating species distribution across the watershed represents a key step towards understanding the resource and promoting protection and restoration of mussels. The protection and restoration of freshwater mussels is included in the Chesapeake Bay Watershed Agreement, yet CBPP Management Strategies and Work Plans have yet to address freshwater mussels (https://www.chesapeakebay.net/managementstrategies/). Because freshwater mussels are not included in action plans, they have yet to be considered a priority funding subject by NFWF limiting mussel restoration opportunities. The consensus of workshop participants was that freshwater mussels should be included within future work plans and future funding efforts.

Table 1.1 Mussel species supported by the Chesapeake Bay states within the major drainages of the Chesapeake Bay. This list was generated by referencing peer-reviewed journal articles and state wildlife agency data sets. YES indicates the historic records of the species exists within the bay drainage of the state, or within the basin listed. NO indicates, the species does not exist in the bay drainage of the state (although it may exist in the state outside the bay drainage).

Genus	Species	Common Name	Federal Status	VA	MD	DC	DE	WV	PA	NY	James	York	Rapp.	Pot.	Susque.
Alasmidonta	*heterodon*	Dwarf Wedgemussel		YES	YES	YES	YES	NO	YES	NO	YES	YES	YES	YES	YES
Alasmidonta	*undulata*	Triangle Floater		YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Alasmidonta	*varicosa*	Brook Floater		YES	YES	YES	YES**	YES	YES	YES	YES	NO	NO	YES	YES
Alasmidonta	*marginata*	Elktoe		NO	NO	NO	NO	NO	YES	YES	NO	NO	NO	YES	YES
Anodontoides	*ferussacianus*	Cylindrical Papershell		NO	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO	YES
Elliptio	*complanata*	Eastern Elliptio		YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Elliptio	*congaraea*	Carolina Slabshell		YES	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	NO
Elliptio	*fisheriana*	Northern Lance		YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES
Elliptio	*Icterina*	Variable Spike		YES	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	NO
Elliptio	*lanceolata*	Yellow Lance		YES	YES	NO	NO	NO	NO	NO	YES	YES	YES	YES	NO
Elliptio	*producta*	Atlantic Spike		YES	YES	NO	NO	NO	NO	NO	YES	YES	YES	YES	NO
Elliptio	*roanokensis*	Roanoke Slabshell		YES	NO	NO	NO	NO	NO	NO	NO	YES	YES	NO	NO
Elliptio	*angustata*	Carolina Lance		YES	NO	YES	NO	NO	NO	NO	YES	YES	YES	YES	NO
Fusconaia	*masoni*	Atlantic Pigtoe		YES	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO
Lampsilis	*cardium/ovata*	Pocketbook		YES	YES	NO	NO	NO	YES	NO	NO	NO	NO	YES	NO
Lampsilis	*cariosa*	Yellow Lampmussel		YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES
Lampsilis	*radiata*	Eastern Lampmussel		YES	NO	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES
Lasmigona	*compressa*	Creek heelsplitter		NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	YES
Lasmigona	*subviridis*	Green Floater		YES	YES	YES	YES**	YES	YES	YES	YES	YES	YES	YES	YES
Leptodea	*ochracea*	Tidewater Mucket		YES	YES	YES	YES	NO	NO	NO	YES	YES	YES	YES	YES
Ligumia	*nasuta*	Eastern Pondmussel		YES	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES	YES
Margaritifera	*margaritifera*	Eastern pearlshell		NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	YES
Pleurobema	*collina*	James Spinymussel		YES	NO	NO	NO	YES	NO	NO	YES	NO	NO	NO	NO
Pyganodon	*cataracta*	Eastern Floater		YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Pyganodon	*grandis*	Giant floater		NO	NO	NO	NO	NO	NO	YES*	NO	NO	NO	NO	YES*
Strophitus	*undulatus*	Creeper		YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Utterbackia	*imbecillis*	Paper Pondshell		YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES
Utterbackiana (previously Anodonta)	*implicata*	Alewife Floater		YES	YES	YES	YES	NO	YES	NO	YES	YES	YES	YES	YES
	: Endangered		Bay Waters	VA	MD	DC	DE	WV	PA	NY	James	York	Rapp.	Pot.	Susque.
	: Threatened	TOTAL:	28	23	16	15	11	12	15	13	18	18	18	21	18

**Giant floater is not expected to occur in the Upper Susquehanna basin, however NYSDEC found individuals in the Canisteo River that clearly had nodulous beak sculpture like we would expect with giant floater. Right next to these other individuals were observed with non-nodulous beak sculpture (we called these eastern floater) and still others with one nodulous valve and none non-nodulous valve. Acknowledging uncertainty, NYSDEC has been lumping all questionable records as Pyganodon sp.*

***Brook Floater and Green Floater are expected to be locally extinct from Delaware waters but historic records have been observed.*

Table 1.2: Mussel Databases and contact information

Agency/ Organization	Geographic Distribution	Contact	email / website
DCR- Natural Heritage	VA	Renee Hypes	rene.hypes@dcr.virginia.gov
Maryland Department of Natural Resouces	MD	James M. McCann Zoologist, Wildlife & Heritage Service Department of Natural Resources UMCES Appalachian Laboratory 301 Braddock Rd., Frostburg, MD 21532 301-689-7105 (office)	james.mccann@maryland.gov
West Virginia Division of Natural Resources	WV	brian.p.streets@wv.gov	brian.p.streets@wv.gov
Carnegie Museum of Natural History	NY	Timothy A. Pearce, Ph.D., Curator of Collections & Head, Section of Mollusks 4400 Forbes Ave, Pittsburgh, PA 15213-4080, USA ph 412-622-1916; fax 412-622-8837	pearcet@carnegiemnh.org
New York Natural Heritage Program	NY	Erin White, Zoologist and Project Coordinator 518-402-8955	elwhit02@esf.edu
PA Natural Heritage Program, Western Pennsylvania Conservancy	PA	Mary Walsh, Pennsylvania Conservancy	mwalsh@paconserve.org
New York Department of Environmental Conservation	NY	Amy Mahar Biologist, Division of Fish and Wildlife New York State Department of Environmental Conservation 6274 East Avon-Lima Rd, Avon, NY 14414 P: (585) 226-5337 | F: (585) 226-6323 |	amy.mahar@dec.ny.gov
Nature Serve	Global		https://www.natureserve.org/
Invertebase	Global		http://www.invertebase.org/portal/collections/index.php
Indigbio	Global		https://www.idigbio.org/portal/search
Global Biodiversity Information Facility	Global		https://www.gbif.org/

Section 2. Ecosystem Services Provided by Mussel Populations

Protecting ecosystem services (i.e. the benefits people obtain from ecosystems), represents an important component of Chesapeake Bay restoration goals. Ecosystem services include provisioning, regulating, cultural and supporting services (Millennium Ecosystem Assessment, 2003, 2005). Freshwater mussels provide a variety of ecosystem services, some of which are similar to those provided by oysters. These include removal of suspended and dissolved material from the water column (or sequestration), habitat creation, and bio-indication. Additionally, there are cultural and existence services (i.e. the value that people place on an item merely to know that it exists) associated with freshwater mussels (Strayer, 2017). Several peer-reviewed studies and literature reviews have outlined these benefits (Vaughn, 2018; Spooner, and Vaughn, 2006). Still, questions remain regarding the magnitude of present and past levels of ecosystem services provided by mussel populations in the Chesapeake Bay Watershed and whether these services can be increased sufficiently to help address watershed management goals via mussel protection and restoration. The 2009 Executive Order 13508 encouraged the protection and restoration of shellfish as an important pathway to consider in the management of watersheds, however shellfish restoration has been focused primarily on oysters.

At the workshop there was some divergence of opinions in the role freshwater mussels should play in the context of nutrients. On one hand, several participants expressed that because mussels enhance nitrogen removal, and as such crediting these services should be formalized in order to provide incentives to their protection and restoration. Alternatively, other participants expressed their view that nutrient benefits are likely marginal and raised concerns about potential effects of mussel restoration for the purpose of nutrient removal (i.e. decreased attention on biodiversity, genetic variation, etc.). Here we provide a detailed explanation of what is known about the influence of mussels on nutrients and challenges that need to be considered by the partnership.

Nutrient effects

Freshwater mussels have the capacity to improve water quality through filter feeding whereby suspended particles, including particle-bound pollutants (nutrients and other contaminants), can be removed from the water column. By removing particulate matter (i.e., seston) from the water column, mussels may improve water clarity, providing more light for benthic producers such as submerged aquatic vegetation (Strayer, 2017) and benthic algae. Still, caution is warranted when interpreting such benefits. Mussels may change concentrations of suspended particles and improve water clarity, but they don't always do so. Mussel activity may be too small or other processes in the ecosystem may be too large for mussels to have effects. There are instances of abundant bivalve populations, with substantial clearance rates, failing to alter water clarity (Strayer et al., 2019). Particle-bound nitrogen and phosphorus are also filtered by mussels. Filtration volume depends on the pollutant concentration in the seston, seasonal temperature, hydrodynamic processes, and the biomass, physiological rates, and spatial density of the mussels.

Filtration by mussels represents the gross removal of particles and associated pollutants from the water column. The net removal of nutrients depends on the fate of the filtered matter and the time span being considered. Nutrient removal can be temporary (i.e. re-released upon excretion) or permanent (i.e. accelerated denitrification through benthic modification). Nutrients may also be stored in mussel tissues, shells or in other benthos, which could reduce downstream nutrient delivery during periods of population growth, i.e., until reaching a steady state when removal is balanced by return via death and decomposition. Filtered nutrients can also be transformed or exported via trophic relationships when mussels are consumed by predators and their biodeposits are consumed by diverse benthic organisms. (Allen et al., 2012; Atkinson et al., 2014; Lopez et al., 2020).

The ecosystem services provided by freshwater mussels have been documented in peer-reviewed publications, yet uncertainty remains about the scale and variability of these benefits relative to other shellfish. Uncertainty arises from variability related to filter-feeding, biodeposition, and biogeochemical influences of freshwater mussels in fluvial environments. Some of these parameters have not been as rigorously investigated as their marine counterparts; but also because the amount and nature of ecosystem services provided by freshwater mussels depends on the biomass, size structure, and species composition of the mussel community and the characteristics of the ecosystem. Riverine ecosystems are highly dynamic in temperature, flow, suspended material etc. making it difficult to determine *when* mussel influences are most active. Community composition and diversity can also affect rates of ecosystem services (Atkinson et al., 2018). Furthermore, there is a dearth of information on the location and biomass of populations throughout the Chesapeake Bay watershed which makes it difficult to model these effects across the watershed. Despite efforts to survey mussels in the Bay, current and historical abundance is not well understood in most areas. The Chesapeake Bay watershed has over 25 species of freshwater mussels, but most studies on ecosystem services have focused on only a few species. While some studies have begun to investigate how services vary among species, only a small portion of the entire mussel fauna (primarily Ohio River basin species) have been represented. Few studies have examined how they compare to marine or estuarine bivalves like oysters (e.g., Kreeger et al., 2018).

Freshwater mussels have complex impacts upon the transport of nutrients through rivers and streams. Like oysters, freshwater mussels filter microscopic particles (generally 5-50 µm diameter) indiscriminately (Riisgard, 1988), which is why they can influence water clarity. A relatively small portion (15-35%) of ingested particles is assimilated into the animal's tissue and shell while the majority of this material (typically 50-70%) is released as biodeposits that collect on the bottom of the waterbody, or is released as dissolved or gaseous waste (10-25%) (Bayne and Newell, 1983; Kreeger, 2011). The influence mussels have upon nutrients may not match influences upon bulk material due to adaptations (Hawkins, et al, 1986; Kreeger, 1993; Kreeger et al., 1995). N and P content of feces is typically lower than ingested material. The proportion of ingested nutrients which are excreted as dissolved ammonia varies widely among species (Bayne and Newell, 1983; Kreeger, 1993, 2011; Atkinson et al., 2020).

The timespan that filtered nutrients are removed from the system can also vary widely depending on how they are processed by mussels. For the purposes of nutrient management in the Chesapeake Bay, the greatest interest is expected to focus on long-term or permanent processes such as the enhancement of denitrification processes (e.g. Hoellein et al., 2017).

The incorporation of nutrients into shells or refractory biodeposits that can be sequestered via burial may also represent long term sequestration although these effects are still likely temporary (years to decades) rather than permanent (Strayer and Malcom, 2007). Since denitrification is the only known permanent removal pathway for nitrogen that is mediated by mussels, workshop participants focused on these services.

Denitrification enhancement

Denitrification is the process whereby nitrate is converted to dinitrogen (N_2) gas, and thus prevents delivery to downstream aquatic ecosystems. Denitrification rates are affected by a wide range of factors. At its most basic, denitrification requires a source of organic material and nitrate, and can be limited by nitrification which is commonly driven by nitrifiers attached to oxic surfaces. Many fresh waters receive high loadings of nitrate from sources other than nitrification (e.g., fertilizer, atmospheric inputs) which may alleviate nitrification controls of denitrification. There also must be conditions with and without oxygen in close proximity; thus, bioturbation can play a significant role. In through-flowing water, transferring nitrogen containing particles to the benthic realm increases the potential for denitrification to occur.

In brackish-water systems, oysters (Kellogg et al., 2013) and Atlantic ribbed mussels (Bilkovic et al., 2017; Zhu et al., 2019) have been shown to enhance denitrification. Freshwater mussels have received recent research attention surrounding the potential for denitrification. Several mechanisms have been proposed to explain how mussels might enhance denitrification although this is an area of emerging research and important questions remain. First, mussels influence local benthos by concentrating labile organic matter in the form of biodeposits, potentially diversifying microbial populations within mussel beds. Second, mussels supply ammonia through their excretion introducing a highly reactive form of N and chemically altering the stream sediments. Finally, mussels provide a source of bioturbation, which might enhance microbial activity (Welsh & Castadelli, 2004).

The impact of mussels upon nutrient cycles, and their capacity to enhance denitrification has been suspected by ecologists for a long time, (e.g. Gardner et al., 2001). Three recent studies have documented denitrification enhancement by native freshwater mussel populations (Benelli et al., 2017; Hoellein et al., 2017; Nickerson et al., 2019). (Table 2.1). The studies include six different species and occurred under a range of nitrate concentrations, mussel size and density within the chambers. Variation of denitrification estimates ranged from 1-2 orders of magnitude. Turek and Hoellein (2015) also evaluated the non-native clam *Corbicula* which represent much smaller organisms (0.044 g per individual) and found denitrification rates per g of dry mass (DM) [20-50 µg N (g DM)$^{-1}$ h^{-1}] that were within the range reported for the native species.

There is substantial uncertainty surrounding these estimated effects, and how they vary across several different gradients. Further, these studies include a variety of different methods and occur in geographies and often in species found outside the Chesapeake Bay watershed. In mussel beds, the role of associated fauna, and associated algal populations is not well documented and thus, it is also unclear which of these factors might also influence mussel bed nitrogen dynamics. As such, the proceeding efforts to quantify denitrification rates of freshwater mussels by workgroup participants represent an initial scoping effort which should be improved by ongoing research. Workshop participants acknowledged that there is a distinction between estimating the denitrification rates of existing freshwater mussel populations and assuming denitrification rates would be enhanced by increased stocking of propagated mussels. We explore these caveats in the following sections.

In order to provide context for reported denitrification values we present the following extrapolations, intended to estimate the scale of impact freshwater mussel-mediated denitrification might have upon nitrogen dynamics in the watershed.

Table 2.1. Literature estimates of denitrification enhancement by freshwater mussels within chambers, per individual and per dry mass (DM). These values have been corrected for denitrification that occurs in sediments without mussels.

Species	Study	Mussels per chamber	Soft Tissue per Individual (g DM)	Experiment nitrate Level mg L^{-1}	Control-corrected µg N_2 per m-2 of core	Individuals m^{-2}	µg N_2 individual-1 h^{-1}	g DW soft tissue m^{-2}	µg N_2 flux per g DM^{-1} h^{-1}
Cyclonaias asperata	Nickerson et al. (2019)	1	1.14	0.14	12,334	142.9	86.3	162.9	75.7
Fusconaia cerina	Nickerson et al. (2019)	1	0.94	0.14	11,298	142.9	79.1	134.3	84.1
Lampsilis ornata	Nickerson et al. (2019)	1	2.97	0.14	18,550	142.9	129.9	424.3	43.7
Lasmigona complanata	Hoellein et al. (2017)	1	2.72	12.3	3,600	222.2	16.2	604.4	6.0
Pyganodon grandis	Hoellein et al. (2017)	1	6.1	12.3	6,500	222.2	29.3	1355.6	4.8
Sinanodonta woodiana	Benelli et al. (2017)	1	12.8	0.4-0.7	5,600	31.8	175.8	407.6	13.7

Potential gross impact of mussels upon denitrification

In order to estimate the impacts freshwater mussels have on denitrification across the watershed, a subset of workshop participants utilized the range of values reported in the literature adjusted for key physiochemical conditions and made assumptions about the overall density of mussels across the non-tidal reaches of the watershed (see detailed methods in Appendix C).

Estimating mussel abundance

One of the big uncertainties in estimating the roles of freshwater mussels is knowing the densities (mean densities, maximum local densities, maximum attainable densities) of mussel populations. We don't yet have broad, quantitative surveys of freshwater mussels from representative sites in the basin. As a result, we considered three ranges of abundance to provide some context of the extent these effects might have on nitrogen delivery for the past, present and future. Mussel density has not been broadly characterized, although there are values from peer-review literature and restoration targets that can be utilized for this purpose.

In 1996-1997, Dave Strayer and Andrew Fetterman conducted timed searches of freshwater mussels at 117 sites in streams of the Susquehanna Basin in New York (Strayer and Fetterman 1999). These sites were not selected using a representative or random design, but they were widely distributed through the basin. The sites were not chosen according to their suspected mussel populations, so they may be reasonably representative of streams in the basin, other than ignoring streams small enough to likely not support a mussel population. While the literature does not clearly delineate a threshold under which mussels are supported, generally very small waterbodies (i.e. drainages < 30 sq. km) (Strayer 1993). The data collected were catch per unit effort (CPUE) of mussels, usually based on snorkeling surveys. It is possible to roughly convert these CPUE data into density data using Strayer et al. 1997 which calibrated CPUE data against mussel density data from quadrats across a wide range of sites. Susquehanna CPUE data were converted into densities using a ln-ln regression from the data of Strayer et al. (1997) and correcting for back-transformation bias as described by Sprugel (1983). The average CPUE across the 117 sites was 19.3 mussels/hour, but the data were highly skewed (see Figure 2.1), with a median of 4 mussels/hour. Likewise, the estimated densities are highly skewed, with a mean of 0.85/m^2 and a median of 0.11/m^2. This exercise produces very soft estimates, both because the data are 25 years old and because the CPUE-to-density conversion is approximate.

Figure 2.1. Mussel Survey results Catch Per Unit effort(no./hr) and Estimated Density (no/m2) from Dave Strayer and Andrew Fetterman from 1996-1996 for Susquehanna Basin in New York

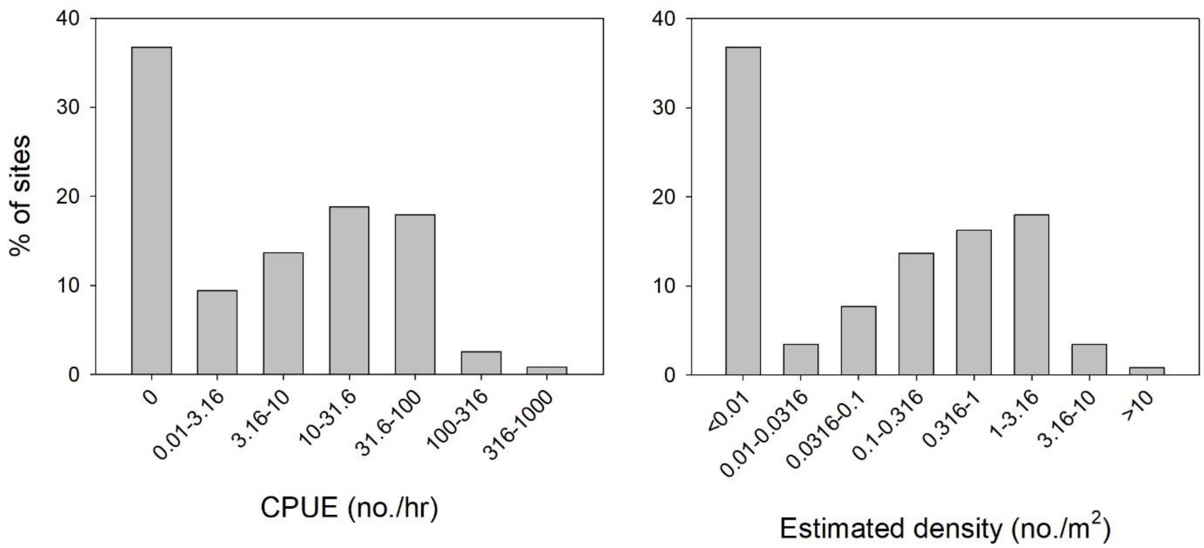


Figure 2.1 Histograms of catch per unit effort and associated estimated density from Strayer and Fetterman, unpublished data.

Other data sets point to similar ranges of abundances, although focused on identified mussel beds rather than independently of mussel habitat. The range for existing mussel beds in Broad Run (VA) and the Cacapon River (WV) have been estimated at 2-3 individuals m^{-2} and were used to establish restoration targets of 5 individuals m^{-2} as documented in the DuPont/South River NRDAR (USFWS, 2017). Outside the watershed, others have suggested higher restoration targets (25 individuals m-^{2}) (Jones et al., 2018). Higher densities of mussels (up to 100 individuals m^{-2}) have been observed in other watersheds (Allen and Vaughn, 2010; Sansom et al., 2018). Recent studies have found important ecosystem effects associated with densities of 25 individuals m^{-2} (Sansom et al., 2018) which add an additional element of uncertainty and suggest that high density beds may have synergistic effects. Ultimately, there is substantial uncertainty associated with historic and current density of mussels, but we utilized these values as a framework for estimating the potential of mussel influence upon nitrogen loads.

First, we utilized a range of 1-10 mussels m-^{2} to represent a Pre-Colombian basin-wide Chesapeake Bay. This follows Strayer (2014) for the Interior Basins, although these basins may have higher mussel carrying capacities than the Atlantic Slope. These are ultimately based upon best professional judgement but are consistent with other peer review literature.

Second, we utilized a range of 0.01 to 1 individuals m^{-2} to represent current mussel densities across the basin. This range is supported by surveys by Dave Strayer and Andrew Fetterman (Figure 2.1) from the 1990s which had a mean of 0.85/m^2 and a median of 0.11/m^2. This effort excluded many small streams which may not support mussels and occurred in region which had not been severely degraded due to acid mine drainage. There are likely sub-watersheds with mussel densities closer to the higher end of the range. Still there are also likely substantial reaches where mussels are no longer supported due to degradation (e.g. acid mine drainage, dams) or where perhaps mussels were never present (e.g. particularly in very small streams). Highly skewed distribution of mussel densities across sites indicate that the basin-wide average density (and any ecosystem services that depend on that density) is determined by a small number of high-density sites. This suggests that **any future surveys designed to estimate ecosystem services should focus on estimating densities and extent of high-density sites**. Two-stage sampling designs may be especially helpful here

Finally, we utilized a range of 10 to 100 individuals m^{-2} to represent densities of densely populated mussel beds. Within the Chesapeake Bay Watershed there are observations of mussel beds with densities around 25 m^{-2} (Kreeger et al., 2013; Strayer personal communications). Observations nearing 100 individuals m^{-2} have occurred outside the watershed (e.g. Rankley et al., 2019; Sanson et al., 2020). These dense mussel beds are rare and likely represent a small proportion of mussel observations, although they are likely important to overall abundance and effects.

Applying denitrification rates to mussel densities

We made assumptions about mussel mass and applied those to the densities cited. For an average or typical mussel mass we used 1 g per individual based on Strayer et al., 2014. For an upper bound we assumed 1.64 g per individual based upon survey data (n = 1600) from the Delaware estuary (Kreeger, unpublished data).

For simplicity, we developed estimates specifically for the Susquehanna River watershed, a major tributary to the Chesapeake Bay, where we utilized data on water quality and temperature regimes. Estimates are expected to differ in other tributary watersheds due to various physiochemical factors (e.g. temperature, background nitrate levels). We utilized low, moderate and high denitrification rates and densities and applied corrections for temperature and nitrate levels, as detailed in Appendix C

The results of these modeling exercises suggest that during the pre-Colombian era, freshwater mussels (with assumed densities of 1-10 individual m^{-2} across the basin)would have had net denitrification effects ranging from 39,000 lbs. to 11.4 million lbs. nitrogen per year (Figure 2.2). This corresponds to 0.015 to 7.9% of current nitrogen loads for the Susquehanna River**. These estimates are intended to represent what pristine Chesapeake Bay Watershed mussel populations might have achieved**.

Current mussel abundance (and the corresponding ecosystem services) is likely much lower as a large proportion of waterways no longer support mussel populations. Assuming an abundance range of 0.01 – 1 individuals m^{-2} across the watersheds, and the same denitrification rates, we estimate current populations might provide net denitrification rates that range from 396 lbs. to 1.1 million lbs. This corresponds to 0.0003 to 0.79% of current nitrogen loads for the Susquehanna River**.** These wider ranges of values are predicated both on the uncertainty about density, as well as the uncertainty about denitrification effects.

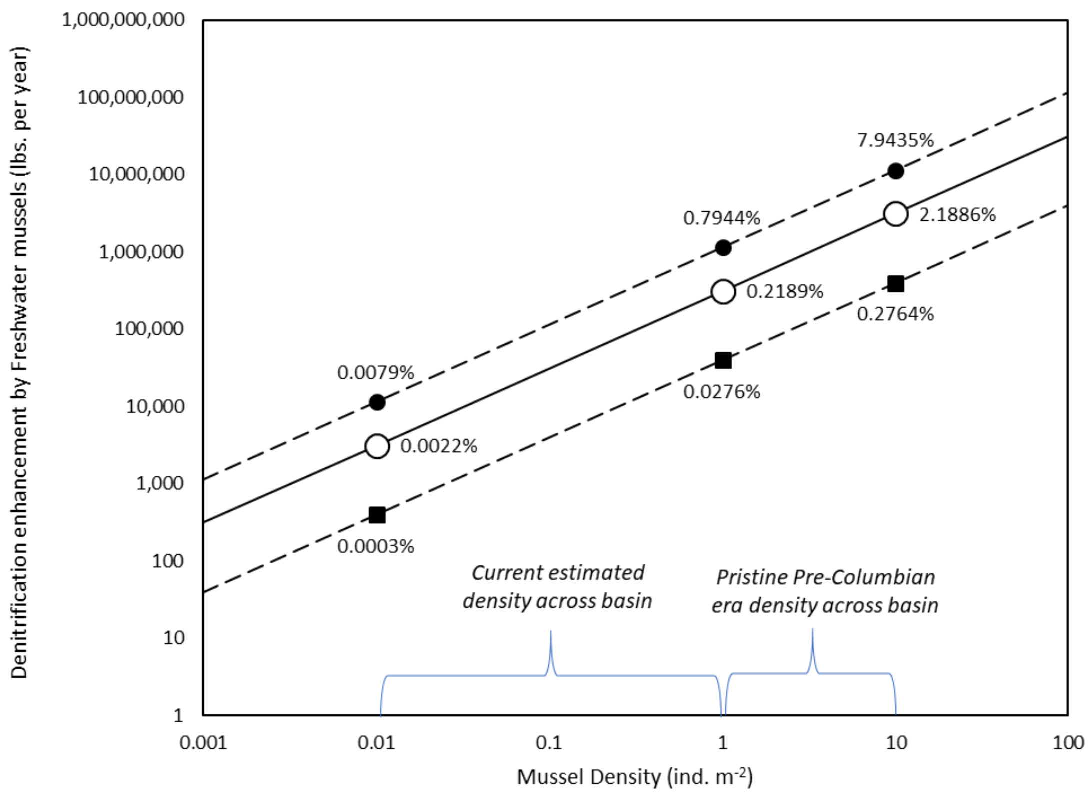


Figure 2.2 Estimates of mussel mediated denitrification (DNFm) across the Susquehanna River Basin, at various assumed abundances and literature reported denitrification rates. High (dot), average (circle), and low (square) estimates are based on the maximum, average, and minimum literature rates of DNFm per g DM, respectively, as reported in Table 2.1, after applying concentration and temperature adjustments. The high estimates are based on an average mussel size of 1.64 g per mussel. The low and average estimates are based on an average mussel size of 1.0 g per mussel. Data Labels represent percent effects relative to current nitrogen loads at Conowingo, PA in the Susquehanna River.

Denitrification comparison between mussel beds and oyster reefs

Based on the modelling results from the previous section, a comparison was made between estimates of denitrification in freshwater mussels with literature-reported nitrogen removal potential for oysters (Kellogg et al., 2013, Lunstrum et al., 2018, Westbrook et al., 2018). Given the focus of oysters by the partnership, we felt this exercise could be useful in contextualizing the contributions of freshwater mussels.

We utilized a range of 10 to 100 individuals m^{-2} to represent densities of densely populated mussel beds. These estimates are intended to estimate the benefits a well-established mussel bed can have on nitrogen loads. Densities this high are not seen commonly but are aimed at evaluating the benefit of a densely populated mussel bed based on current understanding. We estimate a range of denitrification rates following the methods outlined in Appendix C and the denitrification rates from the studies in Table 2.2.

Denitrification rates associated with oyster reefs have been reported as areal rates with variability across systems. Kellogg et al. 2013 reported denitrification rates exceeding 16,000 µg N m^{-2} h^{-1}, but other studies have documented lower denitrification rates. Lunstrum et al. 2018 reported areal rates that were more than an order of magnitude lower. Westbrook et al. 2019 recently found some oyster reefs did not enhance denitrification in oyster reef - marsh complexes in Louisiana.

The results suggest that a dense mussel bed spanning 100 m^2 with a density of 10-100 ind. m^{-2}, would reduce from 0.75 to 7.5 lb N 100 m^{-2} yr^{-1} (Figure 2.3). In comparison, an oyster reef of the same size, might reduce from 0.2 to 13.2 lb N yr^{-1}. Considering maximum observed denitrification rates (rather than the median rates) would yield levels within an order of magnitude (see error bars on Figure 2.3).

While the comparison between mussels and oysters is informative, such a comparison is not ideal: mussel beds and oyster reefs differ in density, geography and size of individuals and research methods have differed between these groups of bivalves. In the referenced oyster studies, sediment integrity of chambers is maintained, and therefore includes denitrification influences from any associated macrofauna in addition to oysters. Unfortunately, this approach has not yet been applied to freshwater mussels. Further, our comparisons only consider denitrification effects, whereas the Oyster BMP expert panel reports have also documented reductions related to oyster harvests. Freshwater mussels which are not harvested in the Bay watershed, don't have a direct analog.

With those caveats stated, the comparison leads to a few conclusions. First, the variability between systems and conditions represents a significant challenge to quantifying these ecosystem services and incorporating them into management actions. Second, the denitrification effects of mussel beds and oyster reefs appear to be similar (within 1-2 orders of magnitude), although oysters, which are more likely to exist at high areal densities due to their reef structure, may have higher areal rates (Figure 2.1). Mussels are generally less densely populated than oysters but may be more broadly distributed, and thus, may offer benefits across a larger geographic scale. Since mussels occur in freshwater and the upper portion of the watershed, they may also reduce nitrogen pollution prior to it entering the estuary.

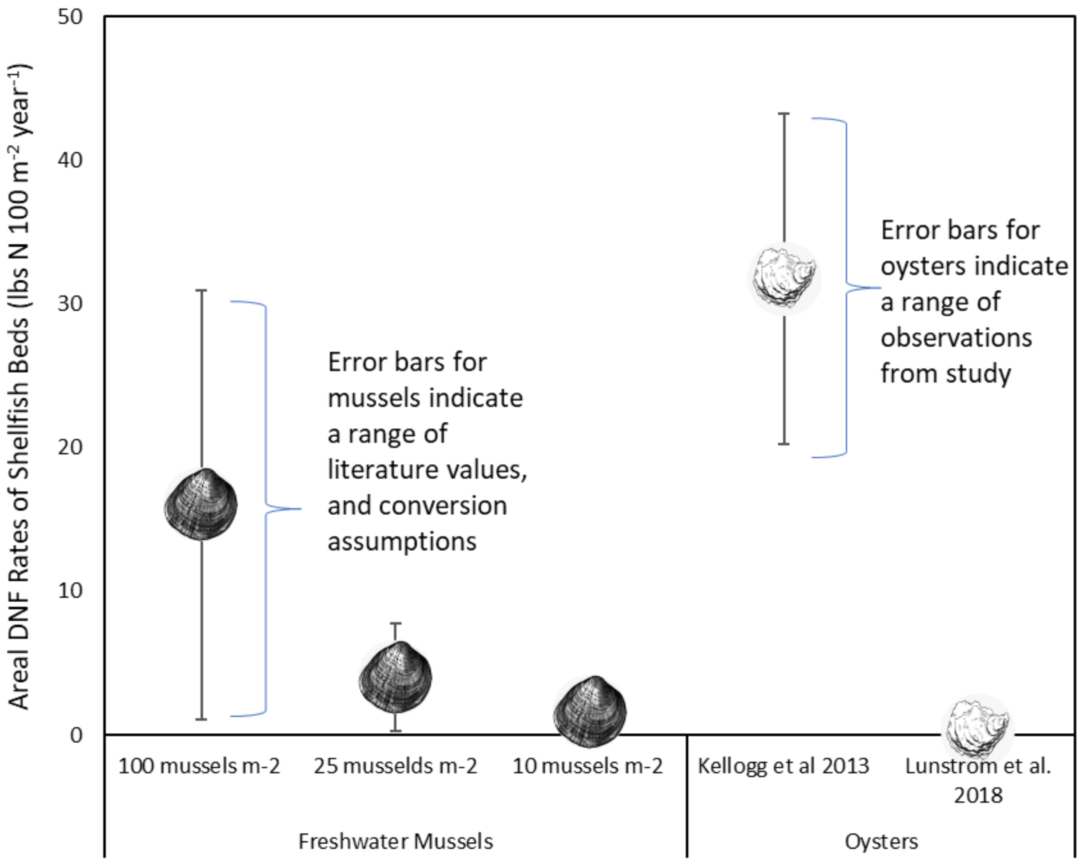


Figure 2.3 Comparison of Estimated Denitrification effects of mussel beds and oyster reefs.

Providing context for the scale of mussel effects with CAST

These gross impact results suggest that across a range of mussel densities, freshwater mussel-mediated denitrification is unlikely to be a dominant force controlling nitrogen transport in the Chesapeake Bay Watershed. However, these estimates also show this effect may not be trivial and could be viewed comparable to some other management efforts. For additional context and scale, we utilized the Chesapeake Assessment Scenario Tool (CAST) to consider progress numbers across sectors and remaining goals for the watershed. Historically, the Bay watershed has achieved a 24% reduction in nitrogen loads (1985-2018) and needs an additional 19% reduction in nitrogen to achieve bay restoration goals. Several non-point source sectors (e.g. Stormwater, Septic) have had very small percentage decreases (<1%) while others have shown increases.

Our estimates suggest current mussel density provide a net benefit of mussel denitrification of 0.001% to 1.2% of current loads. Estimates of past or future potential losses in mussel abundance would have a substantial effect on buffering capacity. If mussel abundance has in fact declined from ~5 individuals m^{-2} to ~0.5 individuals m^{-2}, we estimate a loss in corresponding natural buffering capacity ranging from 200,000-8,000,000 lbs. of N per year. Likewise, future losses in mussels may continue to degrade this natural assimilative capacity. Some of those losses could have been offset by the introduction of invasive Corbicula which have been shown likely to provide some level of enhanced denitrification.

We utilized a CAST analysis to provide comparisons to modeled land use load. According to these numbers, 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 agricultural or developed land use. Historically, restoration targets in this region have focused on much lower densities (~5 individuals m^{-2}) which would correspond to approximately 15 lbs. of N per acre. To put these number 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.

Thus, the nitrogen benefits of a restored mussel bed appear to be within the range of traditional agricultural BMPs with similar extent. The costs associated with mussel restoration efforts, which likely vary by circumstance, would ultimately determine whether this approach would be competitive. Agricultural practices are typically highly cost-effective, ($1-$100 per lb. N) whereas stormwater retrofits tend to be more expensive, ranging from $100-$10,000 per lb N (Chesapeake Bay Program's Water Quality GIT, 2018). Even if the cost efficiencies are not competitive, this does suggest that efforts to protect or restore mussels have potential to have a tangible level of nitrogen reductions. Evaluations of the costs to enhance mussel populations remains an important consideration. While these estimates suggest future potential of considering mussels in nutrient budgets, several research questions remain. Factors such as mussel density, background nutrient concentrations, other physicochemical parameters (e.g. flow), and species composition may influence denitrification rates, which has important implications for applying these rates across the watershed. Further, the methods utilized to estimate denitrification in general have significant challenges. For instance, sediment structure and co-occurring macrofauna can play an important role in denitrification but to date have not been included in freshwater mussel estimates of denitrification. As a result, workshop participants recommend future research support be directed towards addressing these questions.

Additional ecosystem services

Mussels offer other potentially impactful contaminant export or sequestration pathways that should also be considered by managers, including other forms of pollutants that mussels filter or assimilate (e.g., suspended inorganic nitrogen, phosphorus, pathogens). Research is needed to quantify these processes. Long-term nutrient storage may be more important in large rivers where shells may be more prone to burial. The duration of contaminant sequestration in tissues depends on mussel lifespans and is therefore shorter (decadal) than shell sequestration, but not trivial considering that some mussels can live for well more than 50 years (Haag and Rypel, 2011). Still, the net effect of such sequestration ultimately depends upon mussel biomass. Finally, mussels and their biodeposits can serve as food for other organisms.

In addition, freshwater mussels can serve as habitat themselves or they can improve or modify habitats (Vaughn, 2018; Strayer, 2017). Mussels have the potential to improve water clarity thereby increasing light availability to submerged aquatic vegetation and mussel biodeposits can facilitate nutrient availability to benthic producers. Mussels can also play important roles in food webs by transferring nutrients and energy, some of which may be exported from the system. They play a role as resource subsidies (i.e. transferring nutrients, energy to other ecosystems) and thereby support both aquatic and terrestrial ecosystems. The sensitivity and long life histories enable mussels to be effective bioindicators that can improve our understanding of stream health. Finally, mussels have existence and cultural services. Archaeological records show various tribes of Native Americans utilized freshwater mussels as food sources dating back at least 10,000 years (Haag, 2012).

Restoration of freshwater mussels to promote ecosystem services

Numerous management strategies exist to promote natural populations of freshwater mussels and their associated ecosystem services. Locations where extant populations of freshwater mussels still exist can be prioritized for conservation. Locations where mussel populations have been lost or degraded can be targeted for restoration, via improvements in, or remediation of mussel habitats and in some cases via the reintroduction or enhancement of mussel populations.

Reintroductions or enhancements involving hatchery-reared mussels should be evaluated carefully in advance. Their benefits to ecosystem services should be quantified sufficiently for cost comparison with other restoration strategies. Underlying risks should be considered. These include compromising the gene pools of the natural populations (e.g., Haag et al., 2012; Jones et al., 2006) and the introduction of parasites and diseases (Brian et al., 2021). The habitat or water quality issues that caused the need for restoration should be understood and remediated to assure survival of stocked organisms (Strayer et al., 2019). In many cases, effort directed at habitat and water quality improvement may be the preferable restoration strategy.

Lack of critical data is an important bottleneck for most forms of mussel restoration. Most resource agencies have documented some level of species distribution and abundance throughout their states, which populations are in decline, and which are stable but additional resources to support and expand this work are needed to enhance monitoring efforts. Many mussel surveys are irregular and fail to sample for juvenile mussels, a key component to evaluating mussel population health and persistence. Similarly, there is a lack of available data on what factors have contributed to population decline/loss on a local scale and whether these factors have been sufficiently mitigated to allow for re-colonization (or population augmentation) (e.g. Galbraith et al., 2018). These are critical issues that limit potential to restore mussels and supersede propagation efforts.

Once these factors have been identified, numerous opportunities will emerge for restoring mussel populations either naturally or with human assistance. Because many species rely on highly mobile host fish species (e.g. the American eel, American shad), improvements in water quality and habitat should allow for natural recolonization of many areas. Instances where human intervention is necessary may benefit from scientific advancements in mussel propagation that have occurred in recent decades. The propagation of freshwater mussels involves utilizing host fish or artificial media (i.e. serums) in a mussel hatchery to simulate natural reproduction. Until recently, most mussel hatcheries have focused on restoring rare and threatened species. With rising interest in shellfish-mediated ecosystem services, some hatcheries have begun to produce more common species of mussels with the goal of restoring the natural mussel species assemblage and abundance (Kreeger et al., 2018). Although these efforts have been generating considerable interest, numerous challenges still need to be addressed. Care must be taken to ensure biodiversity is not sacrificed for the sake of enhancing ecosystem services or that rare and endangered species are not further jeopardized by rapid changes to the mussel community. Further, it is important to ensure that propagation does not alter natural genetic diversity and that care is taken to ensure high survivorship among stocked mussels so that massive die-offs do not exacerbate water quality problems. It is also important to consider whether enhancing densities of mussels (via propagation) will lead to additional ecosystem services, based on sufficient habitat and water quality (McMurray and Roe, 2017; Strayer et al., 2019). Propagation provides a way to increase the rate at which recently restored habitat is recolonized. Tools and methods are already developing to manage these risks.

The number of threats facing freshwater mussels is growing and will require increased attention from malacologists and other professionals, as well as additional resources to address these problems. Therefore, resources for recruiting and training biologists to rigorously address these issues pertaining to may be helpful. It may also allow for a way to restock areas where natural fish hosts may be blocked by dams, although the lack of fish hosts would still need to be addressed for long-term success. In many locations, suboptimal habitat conditions may be the greatest constraint on mussel carrying capacity and population size, particularly in urban landscapes and streams impaired by stormwater runoff. In such areas, habitat improvement might be necessary prior to propagation efforts.

Many of these restoration tactics and ecosystem services are new and largely untested. Evaluating the success of habitat improvements and stocking efforts requires revisiting and tracking the restoration sites, and their mussel populations over time. In order to achieve enhancements of ecosystem services, these efforts will require more pilot testing. Additional monitoring will also be required to verify intended outcomes to enhance mussel populations.

Conclusions

Mussels represent an integral component of many freshwater ecosystems and provide a variety of important functions that are rapidly declining with continued mussel loss. Many of these functions could provide significant benefits to humans, particularly water filtration and enhanced denitrification.

Important research questions remain to fully evaluate the potential effects of mussel communities on denitrification and further research is needed to identify ways to sustainably enhance mussel populations to increase denitrification rates in natural ecosystems. We recommend the partnership support research focused on filling these data gaps and developing robust, peer-reviewed estimates of freshwater mussel denitrification rates for the Chesapeake Bay region. Upon filling these research gaps, a BMP expert panel should be convened to evaluate these benefits and potential credits for mussel restoration. The oyster BMP expert panel provides an important model; however, several new questions will need to be address that relate to mussel diversity, life history and conservation status.

Section 3. Prominent Threats to Mussels

Mussel populations are threatened by anthropogenic pressures due to their intricate life history strategy, broad geographic range, diversity, and sessile adult stage. Disruptions in hydrologic connectivity, degradation of habitat and water quality all have prominent influence upon mussel populations. These threats overlap with issues that have been considered for the past 35 years in Chesapeake Bay restoration efforts. Table 3.1 illustrates the most prominent intersections between threats as evaluated by this workgroup and Chesapeake Bay restoration efforts.

Chesapeake Bay restoration has sparked a diverse set of management efforts through incentives and regulatory approaches. These strategies are primarily directed toward nutrient or sediment removal but also provide other benefits and have other external consequences. A previous STAC Workshop (McGee, 2017) established a framework focused upon evaluating the co-benefits of nutrient removal strategies, which have been expanded upon as engagement tools. Mussel outcomes were not included in that initiative, but we provide supplemental information to incorporate consideration of mussels. We also explore the impact of management efforts upon mussels which need guidance to ensure that restoration efforts are optimized to benefit and protect mussels. Here we provide brief descriptions of degrading forces to mussels.

Table 3.1 Summary of topical intersection between threats to freshwater mussels and 2014 Chesapeake Bay Watershed Agreement initiatives

Threat to freshwater mussel populations	2014 Chesapeake Bay Watershed Agreement (CBWA):	Corresponding GIT Engagement	Corresponding GIT workgroup
Hydrologic Connectivity: Dams, Channelization, Culverts all disrupt habitat and potentially prevent fish hosts from reaching gravid mussels and dispersing juveniles	CBWA lays out specific goals for migratory fish populations which include improving **hydrologic connectivity.**	Vital Habitats	Fish Passage, Fish Habitat Action Team
Climate Change and Hydrologic alteration: Climate change, which is likely to disrupt and alter hydrologic systems represents a threat to mussels and their habitat.	CBWA has a goal to "Increase the **resiliency** of the Chesapeake Bay watershed, including its **living resources, habitats,** public infrastructure and communities, to withstand adverse impacts from **changing environmental and climate conditions.**	Water Quality, Vital Habitats	Fish Habitat Action Team, Climate Change Resiliency
Ammonia (Nitrogen): Ammonia represents the most prominent nutrient impact to mussel populations; In 2013, EPA established Water Quality Criteria to protect sensitive life stages of freshwater mussels.	CBWA and the Chesapeake Bay Total Maximum Daily Loads specifically cite needed **nitrogen** reductions to improve attainment of Chesapeake Bay water quality standards	Water Quality	Wastewater

Toxics: Freshwater mussels are sensitive to a wide variety of toxic pollutants including PAHs, pesticides, Heavy Metals, and Chloride.	CBWA specifically contemplates addressing **toxics** by establishing a goal to "Ensure that the Bay and its rivers are free of contaminant effects on living resources and human health"	Water Quality	Toxic Contaminant
Habitat Loss: Tremendous losses in habitat have degraded freshwater mussel populations	CBWA established a goal to continually improve effectiveness of fish **habitat** conservation and restoration efforts by identifying and characterizing critical spawning, nursery and forage areas within the Bay and tributaries for important fish and **shellfish**	Sustainable Fisheries	Fish Habitat Action Team
Stewardship: Freshwater mussels lack public awareness that is likely to yield significant shifts in public policy.	CBWA established goals to increase the number and the diversity of local citizen stewards and local governments that actively support and carry out the conservation and restoration activities that achieve healthy local streams, rivers and a vibrant Chesapeake Bay.	Stewardship GIT	Citizen Stewardship, Education

Dams

Large-scale dam construction has profound effects on freshwater mussel communities and operations of existing dams continue to impact both upstream and downstream mussel populations. Dams are considered by many researchers to be the primary cause for the rapid and widespread decline of mussels world-wide, although the mechanisms driving species loss are numerous and interacting (Layzer et al., 1993; Watters, 1996; Vaughn and Taylor, 1999; Watters, 2000; Haag, 2012). Dam-related habitat destruction, alterations to flow regime, temperature, water quality and quantity, loss of host fish, loss of connectivity among mussel and host fish populations, and changes in food availability have all been implicated in mussel decline.

The most evident impact that dams have had on native mussel fauna has been caused by the conversion of thousands of miles of high-quality, free-flowing rivers and streams to lakes and ponds (Bogan, 1993; Watters, 1996, 2000). The majority of unionid species evolved in moving water, with a small subset of species that are lake- and pond-adapted. Unlike riverine conditions, lake habitats are associated with conditions that do not favor mussels (Watters, 1996, 2000). These conditions have eliminated mussels from many, deeper impoundments. In shallower reservoirs, some species of lentic mussels can be found, but generally in low densities (Haag, 2012).

Unnatural flow and thermal regimes caused by dam releases can result in unsuitable habitat for both mussels and their host fish miles downstream of dams (Layzer et al., 1993; Vaughn and

Taylor, 1999; Galbraith et al., 2010). Rapid fluctuations in flow can leave mussels stranded out of water or dislodge them from the sediment, washing them downstream. Coldwater releases can lead to unseasonal temperature regimes that disrupt spawning cues, feeding rates, and overall body condition (Watters, 2000; Galbraith and Vaughn, 2011). Dam releases can also cause drops in dissolved oxygen and can alter the quantity and quality of food particles available for downstream mussel communities (Layzer et al., 1993; Watters, 2000; Hornbach et al., 2014).

Systematic fragmentation of once continuous river systems has isolated what remains of historic mussel populations. This has been especially problematic for mussel species that rely on migratory fish for their successful reproduction (Watters, 1996). Migratory hosts such as American Eel and alosines are unable to navigate around instream barriers like dams and culverts to come into contact with gravid female mussels. This has led to populations of functionally extinct mussels, where adults still survive but are unable to reproduce due to insufficient host fish abundance (Bogan, 1993; Galbraith et al., 2018). Equally important, isolated mussel beds are more susceptible to extirpation from stochastic events because recolonization from nearby populations has been blocked (Newton et al., 2008).

Habitat destruction

Stream channelization, dredging, and in-stream construction can also drastically alter mussel habitat (Aldridge, 2000; Strayer et al., 2004). Increased stream flashiness, sedimentation, resuspension of contaminants and nutrients, and changes in bed stability are all thought to be major factors affecting mussels and their habitat (Watters, 2000). Changes in flow regime represent a systemic threat to mussel habitat that is exacerbated by increases in impervious surface and climate change (Acreman 2014). Addressing flow requirements of mussels is challenging due to their varied habitat requirements and complex life histories (Gates et al. 2015).

Quantifying mussel habitat loss is often a difficult task as there can be subtle differences among species, mussel beds are dynamic and shift throughout given river systems, and existing population distribution (and thereby habitat use) are not necessarily reflective of historic ones (Strayer, 2008). This workshop only touched on these issues, but further attention to improving our understanding of mussel habitat, particularly in the context of water management, is warranted.

Water quality

Freshwater mussel populations are also highly sensitive to water quality as has been documented through several studies and reviews (e.g. Nobles and Zhang 2011). Many of these sensitivities remain poorly understood. In some cases, freshwater mussels have been shown to represent the most sensitive aquatic life to certain pollutants which has led to the development and continued revision of water quality standards. In 2013, EPA developed national ammonia criteria for the purposes of protecting freshwater mussel populations. Wastewater and industrial effluent and the pollutants it contains have been shown to have negative effects on native mussel populations. Salinization as a consequence road salt application, urban runoff, and wastewater spills have also been shown to be problematic for freshwater mussels (Pandolfo et al., 2012 Blakeslee et al. 2013; Robertson et al. 2017). Freshwater mussels are also vulnerable to heavy metals, chlorides, polycyclic aromatic hydrocarbons (PAHs), pharmaceuticals, endocrine disrupting compounds, microplastics, lampricides, molluscicides (applied for zebra mussel control), pesticides, herbicides and other contaminants. Hypoxia, low pH, high pH and turbidity, and high temperature can also threaten mussel populations, particularly during their sensitive juvenile life stages. Degraded water quality throughout the watershed has diminished freshwater mussel populations, thus, improvements in water quality can be expected to enhance future outcomes for mussels.

Other factors threatening mussels

Other factors known to threaten native freshwater mussel species include disease and invasive species The invasive zebra and quagga mussels have had profound impacts on native mussel populations across North America, biofouling them to the point of suffocation, starvation, and complete elimination in many cases (Strayer et al., 1999; Strayer, 2009). Further, zebra mussels can degrade freshwater mussels by simply competing for food (Strayer et al 2018).

Recent studies have showed that Corbicula has strong negative effects on native freshwater mussel populations (Haag 2020). The effects of other invasive aquatic invasive species (e.g. molluscivores such as black carp), may also pose significant threats (Strayer, 1999; Sousa et al., 2008, Moore et al., 2019). Similarly, studies on the prevalence of disease in mussel declines have been rare, but it is being explored further as a potential causative agent of large-scale mussel die-offs (Starliper, 2009). Recent publications have helped elucidate the role of densovirus in mussel die-offs illustrating the potential for pathogens to cause greater harm to freshwater bivalves (Henley et al., 2019; Jordan et al., 2020). These effects are likely exacerbated during periods of suboptimal conditions also requires further evaluation (Grizzle and Brunner, 2009).

Another threat to freshwater mussels has recently been dubbed “enigmatic mussel die-offs”, which represent large-scale mortality that cannot be explained by other known factors (Haag, 2019). These represent large mortality events that cannot be easily explained by other known factors (Haag, 2019). Enigmatic mussel declines have no clear causative agent but have been hypothesized to be the result of combinations of individual stressors, delayed effects of habitat destruction, stochastic processes, pesticides, invasive Corbicula introductions and pervasive changes in water quality (Haag, 2012, Haag 2021). However, what is troubling is that these declines often occur rapidly and in streams with otherwise healthy aquatic communities and high Index of Biotic Integrity (IBI) scores. A recent publication from the Clinch River suggests that viruses may play an important role in declines (Richard et al. 2020)

Finally, future of freshwater mussel populations is largely threatened by the public’s lack of awareness. Section 4 focuses more specifically on this issue, but policy changes that lead to improved protection of mussels are unlikely be successful without a broader understanding by the public and an enhanced sense of stewardship to protect these native animals.

Chesapeake Bay restoration’s influence on mussels

Bay restoration has initiated diverse management actions which have been successful in reducing pollution to the Bay and its tributaries. These efforts have likely benefitted freshwater mussels but have also likely resulted in resource conflicts.

Bay restoration has clearly improved water quality, or at a minimum improved it relative to what it would have been without restoration efforts. Wastewater treatment plant upgrades have reduced nutrients and other pollution, including ammonia discharges, which are particularly detrimental to freshwater mussel populations. Future upgrades – particularly those in the upper regions of the watershed – have potential to continue reducing these stressors. While many large treatment plants have been upgraded, many small facilities remain where ammonia criteria based on toxicity to juvenile mussels have not been achieved. In Virginia, where these criteria were recently adopted, there are an estimated 490 facilities that need to upgrade to achieve these criteria. Adopting and implementing the 2013 National Ammonia Criteria Water Quality Standard, which are based upon freshwater mussels, represents an important opportunity for considering both mussel outcomes and addressing nutrient loads to the Bay. Attaining ammonia criteria is likely to require upgrades to facilities throughout the watershed, however these upgrades will not necessarily be required to reduce total nitrogen (TN) loads which would require additional treatment steps (i.e. denitrification). Still, the process of nitrification represents a significant and expensive step to reducing TN loads and it behooves the partnership to identify incentives to achieve this additional treatment that would reduce total nitrogen loads.

Stormwater runoff controls, which have reduced the impact of construction or addressed stormwater pollution through retrofits, have likely provided some benefit to mussel populations (Archambault et al., 2018). Efforts to manage runoff from construction sites is an existing goal of the partnership that could impact mussel populations. This includes site design to ensure post-construction runoff does not degrade water quality, as well as retrofitting restoration projects designed to address erosion problems from historic development. Improved pre- and post-construction standards may help to protect mussel habitat by reducing local sedimentation and washout, although it is unclear that these standards have provided sufficient protection for mussel populations.

Stormwater retrofits can improve outcomes but may also pose challenges to mussel habitat as well. Since many of these practices focus on addressing energy (and not contaminants) associated with elevated flows from impervious surfaces, these efforts sometimes utilize retention ponds or stabilize banks through stream restoration efforts. While reducing velocity and the associated erosion (benefitting mussel populations), these efforts may also degrade habitat for mussels by hardening, disconnecting, or eliminating habitats. The partnership should pursue guidance to consider how these retrofits can move forward in a way that does not negatively impact mussels, and further look for opportunities for how these practices might improve mussel outcomes.

Addressing pollution from agriculture has largely focused on voluntary practices. Stream buffers and particularly forested buffers improve habitat for freshwater mussels. Livestock exclusion also provides important protection to mussel habitat. Buffers reduce runoff volume, intercept pollutants, and provide shade to streams in agricultural watersheds. Other practices such as cover crops, nutrient management plans, and improved waste storage are also likely to reduce nutrient and animal waste inputs to streams. Still, pesticides and herbicides represent a significant concern for freshwater mussels and many of these practices do not address those pollutants. In summary, efforts to address agricultural impacts have had a positive impact on freshwater mussel population but further exploration is warranted to identify which of these practices are most beneficial and provide guidance on how benefits might be improved.

Conclusions

Freshwater mussels have been plagued by numerous threats, many of which have also degraded the Chesapeake Bay. While some of these threats are being directly addressed by existing bay initiatives, others (e.g. dam removal) have yet to be fully considered and require more research attention. Improved understanding of these threats is needed to guide more sustainable water management across the watershed. There is also a conundrum surrounding the effects of nutrients on freshwater mussels. Nutrient levels in many locations are too high to sustain healthy freshwater mussel populations; yet, mussels themselves may play an important role in nutrient removal. Identifying what baseline water quality parameters are necessary for supporting healthy mussel populations will allow for more efficient mussel recovery and restoration, thereby increasing the potential services mussels can provide to the bay. There are instances when these efforts may be in conflict, or when unifying these efforts may lead to greater overall benefits. For example, stream Restoration efforts that aim to reduce nutrient loads should also evaluate implications for mussels. Similarly, efforts to address ammonia discharges to protect freshwater mussels, may lead to opportunities to reduce nitrogen loads to the Chesapeake Bay. Considering optimal BMPs for mussels, is especially important in areas which drain directly to high density mussel beds. The consensus of the workshop participants was that the partnership would benefit from holistically considering eutrophication and protection of mussels together.

Section 4. Engaging the Public with Freshwater Mussels

Iconic species such as oysters, crabs and Striped Bass have been used to galvanize support for the restoration of the Chesapeake Bay. Yet, these species may not resonate with the majority of watershed residents as does a local species of interest such as the Eastern Hellbender, which recently received attention when it was designated the official Pennsylvania state amphibian (Calvert, 2017). Freshwater mussels have captivating life histories involving unique relationships with fish, and they can improve water quality. Widespread throughout freshwater reaches of the watershed, mussels are symbolic of clean water. The highly imperiled status of freshwater mussels is sounding alarms in the conservation community. Together, these three factors offer a compelling and communicable message, making freshwater mussels an ideal candidate for galvanizing support for restoration of freshwater regions of the watershed.

While many restoration efforts are focused towards mitigating nutrient and sediment loads, several of these efforts also benefit freshwater mussel populations. Thus, improving outcomes for freshwater mussels represents an opportunity to incentivize restoration efforts in upper reaches of the watershed. Public education and outreach on these co-benefits will stimulate broader environmental engagement as well as bring needed attention to a highly threatened and important class of organisms. For these reasons, workshop participants recommend the partnership, and specifically the Stewardship GIT consider utilizing freshwater mussels as a form of mascot, to engage audiences on conservation issues throughout the watershed.

Meaningful Watershed Education Experiences (MWEE)

Several partners in the region have successfully involved citizens in freshwater mussel restoration efforts. The Anacostia Watershed Society partnered with citizens in efforts to raise, restore and release mussels in the Anacostia River (Nirappil, 2019). The Partnership for Delaware Estuary has established an approach for citizen monitoring. The Nature Conservancy in partnership with Virginia Tech, U.S. Fish and Wildlife Service (USFWS), and Virginia Department of Wildlife Resources (VDWR) have involved citizens and decision makers in planting and releasing freshwater mussels into the Clinch River (Tennis, 2018).

There have also been successful efforts to incorporate freshwater mussels into education curriculums. The Ohio River Foundation and the Anacostia Watershed Society have developed ‘mussels in the classroom’ programs which offer hands-on learning experience. Chesapeake Bay Foundation has been developing Online Watershed Learning (OWLs) resources related to freshwater mussels designed for middle and high school classrooms. In Montgomery County, MD, these plans have been utilized in learning series across the county. These opportunities represent valuable virtual learning experiences in communicating environmental issues and should help achieve Student Environmental Literacy and Stewardship Goals. Workshop participants recommend the partnership develop and communicate guidance on how to expand these opportunities. Specifically, such efforts could include developing content for the Bay Backpack to support meaningful watershed educational experiences.

Figure 4.1: Examples of in stream Silo (1-3) and Benthic (4) mussel cages from Partnership for Delaware Estuary (PDE)

Citizen monitoring

Citizen groups throughout the watershed have been trained to conduct macro-invertebrate surveys. However, mussel identification and taxonomy are difficult and present challenges to citizen involvement. There are also concerns about the potential for disturbing sensitive freshwater mussel communities or listed species. Still, there are opportunities to engage citizen monitors that should be explored.

iNaturalist offers a platform whereby citizens can document and report observances. Some other states have reporting programs encouraging citizen surveys (Texas Mussel Watch). Released mussels are often tagged with Passive Integrated Transponders (PIT tags). It may be possible to involve volunteers in efforts to utilize tag readers to find and release mussels in efforts to accomplish mark-recapture studies. Citizen-led oyster gardening has been a very popular and successful endeavor for Chesapeake Bay restoration efforts. Freshwater mussels have the potential to survive in enclosures and have been used at hatcheries as well as in other efforts.

Mussel ecologists have utilized mussel cages for many different reasons including determining site suitability, tracking mussel responses or simply to provide a location to keep propagated mussels until deployed (e.g. Cope et al., 2008). Partnership for the Delaware Estuary, alongside other partners, have developed mussel cages for deploying mussels (See Figure 4.3).   It may be possible to involve citizen monitors in the deployment of mussel enclosures as an approach to determining suitable locations for potential releases. Further, cages may provide biological monitoring information (survival rates) helpful to assessing waters. Although there are challenges to facilitating this process, the consensus of workshop participants was that involving citizen monitoring groups in mussel restoration efforts has potential but needs to be refined with consideration of mussel restoration expertise.

Figure 4.2: Educational display of freshwater mussel shells from the Clinch River

Communications

In addition to hands-on experience, the narrative of freshwater mussels should be a regular focus of Chesapeake Bay communications. These organisms represent a critical component to biodiversity in the watershed, they enhance the watershed through ecosystem services, and they broaden the message of protecting aquatic life across all watershed states. Workshop participant consensus was that increased focus on this subject would beneficial.

Shell replicas

Figure 4.3: 3-D replicas of a freshwater mussel shells.

There is substantial diversity in mussels across even small watersheds and displays of this diversity serve as an important tool to engage the public (Figure 4.2). Yet, there are significant challenges to displaying mussel diversity. Shell collections are hard to access in part because some species are rare, but also because obtaining shells, particularly sensitive species, requires permitting. One idea that emerged from these workshop proceedings is to enhance access to shell replicas through three-dimensional scanning efforts. Mary Jones, a doctoral student at the University of Miami in Ohio, recently completed an effort to develop three dimensional scans of freshwater mussel shells from a few tributaries in the southwestern United States (Jones et al., 2018). Performing these scans and providing them to end-users across the watershed would allow for easy access to shell replicas for $5-$10 per shell to use for outreach, education, and training (Figure 4.3). In many ways, the replicas are easier and probably cheaper to use than real shells, which require a permit to hold, are hard to find (particularly for rare species) and are less durable. This effort would greatly enhance education opportunities related to freshwater mussels. Partners from the workshop, including the Smithsonian Institution, which has a comprehensive collection of shells from across country, and the Chesapeake Bay Foundation are working to pursue funding to develop a comprehensive scanning effort that would facilitate three-dimensional printing of all Chesapeake Bay watershed species, and potentially a national inventory. This represents a relatively low-cost initiative that could substantially enhance engagement on freshwater mussels for years to come.

There are several opportunities, some of which have been outlined here, to engage the public through freshwater mussels. Still, it should not be expected that these outreach efforts can be achieved by current mussel managers which already have overwhelming responsibilities. Partnership leaders should work to identify sources of funding for these efforts across the watershed.

Conclusions

Freshwater mussels could serve to engage the public due to their complex life histories, ecosystem services and biodiversity. This engagement could occur in many places and where other iconic species are absent. Specific opportunities to expand engagement include developing content for the Bay Backpack to support meaningful watershed educational experiences, involving citizen monitors, developing focused communications, and developing displays of biodiversity through shell replicas. The partnership could summarize and highlight the benefits of nutrient removal BMPs upon mussel populations. The consensus of the workshop participants was that expanding engagement around freshwater mussels through these opportunities would strengthen the partnership and benefit freshwater mussel protection. Specifically, these efforts could support achieving goals of the Stewardship Goal Implementation Team which include increasing number and diversity of citizen stewards.

Summary of Workshop Findings and Recommendations

Below we provide a series of programmatic recommendations, which represent specific initiatives the partnership could address, as well as a series of research findings, which illustrates important remaining questions.

Programmatic Recommendations

1. **The partnership's leadership (Management Board, Principles Staff Committee) should work to identify and encourage financial support for directed, quantitative mussel surveys and monitoring, as well as overall mussel protection and education efforts. This should include funding for staff positions and resources for hatcheries to address this work.**
2. **We encourage the partnership to include mussel considerations across various workgroups and GITs. Specifically:**
    a. Address mussel considerations in the next Fish Habitat Action Team's management strategies 2-year Workplan
    b. Incorporate mussel factors into relevant management strategies under the Vital Habitats Goal in the 2014 Chesapeake Bay Watershed Agreement, such as Stream Health and Fish Passage.
3. **We encourage the partnership to utilize comprehensive freshwater mussel restoration strategies, which include but extend beyond propagation and release, as a tool for engagement for freshwater portions of the watershed (See Section 4). The following tasks represent examples of how the partnership could accomplish such engagement:**
    a. The Fostering Chesapeake Stewardship Goal Implementation Team could engage with the Chesapeake Monitoring Cooperative and freshwater mussel conservation experts to develop guidance for citizen science mussel initiatives and promoting Meaningful Watershed Education Experiences (MWEEs) related to freshwater mussels. These efforts would support CBWA Stewardship and Environmental Literacy goals. Specific opportunities are outlined below.
        i. The Chesapeake Monitoring Cooperative could work with freshwater mussel conservation experts to develop guidance for protocols and best practices for non-professionals in using mussels to, perform bio-monitoring, assess potential mussel habitat, or benefit water quality.
        ii. The above experts, along with Water Quality GIT members, could work with the Fostering Chesapeake Stewardship Goal Implementation Team workgroups to identify means to promote engagement activities with mussels. These might include community science initiatives and

integrating freshwater mussels into resources for educators (i.e. through the Bay Backpack) to use as part of student Meaningful Watershed Education Experiences (MWEEs) and their associated stewardship projects. This collaboration would include science partners assisting in delivering training for community stewards and educators. These efforts would support CBWA Stewardship and Environmental Literacy goals as well as contributing to mussel conservation.

b. The CBP Communications Workgroup should feature stories on freshwater mussels to educate local stakeholders in non-tidal regions of the watershed about the value of mussels in the ecosystem
c. The Chesapeake Bay modeling workgroup should include freshwater mussels as part of the co-benefit framework and include these benefits within CAST.

4. **We encourage the partnership to take a more active role in understanding and supporting pertinent freshwater mussel research questions (See Research Findings Below):**
   a. Support, encourage and enhance mussel survey efforts (See Section 1), with specific attention to documenting high density mussel beds, mapping suitable habitat and assessing anthropogenic stressors. This should be implemented through GIT and STAR's Strategic Science and Research Framework and GIT-funded projects.
   b. Enhance research efforts focused on threats to mussels and their habitat including disruptions to flow regime (i.e. timing, magnitude, and duration), loss of hydrologic connectivity, degraded water quality and emerging contaminants.
   c. Address remaining research questions related to freshwater mussels' ecosystem services, particularly enhanced denitrification (See Section 2).
5. **Consider intersections between nutrient mitigation and freshwater mussel restoration (See Section 3)**
   a. Explore collaborative opportunities to achieve nitrogen reductions and address new ammonia criteria through the wastewater workgroup.
   b. The Partnership should consider mussel co-benefits related to restoration efforts and should specifically consider mussel protection and restoration guidelines in the context of traditional stream restoration practices (and other practices that may negatively influence mussels).

Findings and Research Recommendation

1. **<u>Finding</u>: Significant efforts have been made to document mussel populations across the region, yet no aggregated database exists which includes this information. <u>Recommendation</u>: Compile and analyze existing mussel distribution datasets and aggregate into a sharable form (See Section 1).** Explore options for compiling a comprehensive set of current and historic mussel distribution data and aggregate to a level that can be shared broadly (considerate of privacy

concerns). Consider working through the Chesapeake Bay GITs to identify funding and a partner to compile the data, identify gaps and fund small, directed surveys/monitoring. Consider utilizing a currently existing data platform to avoid redundancy. These efforts should be aligned with the Freshwater Mussel Conservation Society (FMCS) National Strategy and USGS Agency level strategy. This effort will help address several critical knowledge gaps including:

    a. Assessing trends in mussel abundance and diversity.
    b. Identifying "hotspots" where mussel protection is most needed.
    c. Determining effects of mussel restoration efforts, and whether best management practices are translating healthier mussel populations.
    d. Improving mapping of the geographic extent of suitable mussel habitat.
    e. Improving records for considerations in the context of damages.

2. **<u>Finding:</u> Recent peer reviewed papers have documented the capability of mussels to enhance denitrification. Still, there have yet to be any studies local to the Chesapeake Bay Watershed. <u>Recommendation</u>: Address research needs surrounding ecosystem services with specific focus on denitrification (See Section 2)**
    a. Add mussel related research needs (i.e. current and potential future capacity for mussels to influence nutrients, sediment, and stream health) to the GIT science needs list. Partner with other watersheds exploring similar issues (e.g. Delaware basin) in order to expand capacity. Specific research needs include:
        i. Identify the influence of mussel species and density, nutrient concentration, flow, and seasonal temperature upon the physiological processing of N, and especially denitrification rates. Studies that focus on native species at biologically relevant densities to the region would be beneficial.
        ii. Continue to improve our understanding of current mussel distribution and abundance, and factors that govern habitat suitability and mussel carrying capacity. Specifically, research efforts are needed to quantify factors that are essential to mussel habitat (e.g. flow, pollutants) and to identify targeted future surveys to test hypotheses about habitat suitability.

References

Archambault, J.M., S.T. Prochazka, W.G. Cope, D. Shea, and P.R. Lazaro. 2018. Polycyclic Aromatic Hydrocarbons in Surface Waters, Sediments, and Unionid Mussels: Relation to Road Crossings and Implications for Chronic Mussel Exposure. *Hydrobiologia* 810, no. 1: 465–76. https://doi.org/10.1007/s10750-017-3101-y.

Aldridge, D. C. 2000. The impacts of dredging and weed cutting on a population of freshwater mussels (Bivalvia: Unionidae). *Biological Conservation,* 95:247-257.

Allen, D. C., & Vaughn, C. C. 2010. Complex hydraulic and substrate variables limit freshwater mussel species richness and abundance. *Journal of the North American Benthological Society*, 29(2), 383–394. https://doi.org/10.1899/09-024.1

Allen, D.C., Vaughn, C.C., Kelly, J.F., Cooper, J.T. and Engel, M.H. 2012. Bottom-up biodiversity effects increase resource subsidy flux between ecosystems. *Ecology,* 93: 2165-2174. https://doi.org/10.1890/11-1541.1

Allen, G. H. and T. M. Pavelsky. 2018. Global extent of rivers and streams. Science 361:585-588. DOI: 10.1126/science.aat0636

Atkinson, C.L., Kelly, J.F. & Vaughn, C.C. Tracing Consumer-Derived Nitrogen in Riverine Food Webs. 2014. *Ecosystems*, 17, 485–496 https://doi.org/10.1007/s10021-013-9736-2

Atkinson, C.L., Sansom, B.J., Vaughn, C.C., and Forshay, K.F. 2018. Consumer Aggregations Drive Nutrient Dynamics and Ecosystem Metabolism in Nutrient-Limited Systems. *Ecosystems* 21, no. 3: 521–35. https://doi.org/10.1007/s10021-017-0166-4

Atkinson, C. L., van Ee, B. C., and Pfeiffer, J. M. 2020. Evolutionary history drives aspects of stoichiometric niche variation and functional effects within a guild. *Ecology*, 101(9):e03100. 10.1002/ecy.3100

Ator, S. W., J. W. Brakebill, and J. D. Blomquist. 2011. Sources, fate, and transport of nitrogen and phosphorus in the Chesapeake Bay watershed-An empirical model. Pages v, 27 p. Scientific Investigations Report 2011-5167. U.S. Geological Survey, Reston, VA.

Bayne, B. L. 1976. Marine mussels, their ecology and physiology. Cambridge, United Kingdom: *Cambridge University Press*. 506 pp.

Benelli, S., M. Bartoli, E. Racchetti, P. Moraes, M. Zilius, I. Lubiene, and El. Fano. 2017. Rare but Large Bivalves Alter Benthic Respiration and Nutrient Recycling in Riverine Sediments. *Aquatic Ecology* 51, no. 1: 1–16. https://doi.org/10.1007/s10452-016-9590-3.

Bilkovic, D.M, M.M. Mitchell, R.E. Isdell, M. Schliep, and A.R. Smyth. 2017. Mutualism between Ribbed Mussels and Cordgrass Enhances Salt Marsh Nitrogen Removal. *Ecosphere* 8, no. 4: e01795. https://doi.org/10.1002/ecs2.1795.

Bogan, A. E. 1993. Freshwater bivalve extinctions (Mollusca: Unionoida): a search for causes. *American Zoologist*, 33:599-609.

Calvert, S. 2017. Students asked lawmakers to honor a salamander. Then things got weird. *The Wall Street Journal*.

Chesapeake Bay Program's Water Quality Goal Implementation Team (GIT). 2018. BMP Implementation: Integrating cost-effectiveness and co-benefits with nutrient efficiency. *Presentation for October Water Quality GIT Meeting*.

Cope, W. G., R. B. Bringolf, D. B. Buchwalter, T. J. Newton, C. G. Ingersoll, N. Wang, T. Augspurger. 2008. Differential Exposure, Duration, and Sensitivity of Unionoidean Bivalve Life Stages to Environmental Contaminants. *Journal of the North American Benthological Society* 27, no. 2 451–62. https://doi.org/10.1899/07-094.1.

Downing, J. A., J. J. Cole, C. M. Duarte, J. J. Middelburg, J. M. Melack, Y. T. Prairie, P. Kortelainen, R. G. Striegl, W. H. McDowell, and L. J. Tranvik. 2012. Global abundance and size distribution of streams and rivers. Inland Waters 2:229-236. DOI: 10.5268/iw-2.4.502.

Environmental Protection Agency (EPA). 2013. Final Aquatic Life Ambient Water Quality Criteria For Ammonia-Freshwater. Notice Document 78 FR 52192.

FMCS (Freshwater Mollusk Conservation Society). 2016. A national strategy for the conservation of native freshwater mollusks. *Freshwater Mollusk Biol. Conservation*, 19:1–21.

Galbraith, H. S., D. E. Spooner, and C. C. Vaughn. 2010. Synergistic effects of regional climate patterns and local water management on freshwater mussel communities. *Biological Conservation*, 143:1175-1183.

Galbraith, H. S., and C. C. Vaughn. 2011. Effects of reservoir management on the abundance, condition, parasitism and reproductive traits of downstream mussel populations. *River Research and Applications*, 27:193-201.

Galbraith, H.S., Devers, J.L., Blakeslee, C.J., Cole, J.C., St. John White, B., Minkkinen, S. and Lellis, W.A., 2018. Reestablishing a host–affiliate relationship: migratory fish reintroduction increases native mussel recruitment. *Ecological Applications*, 28(7), pp.1841-1852.

Gardner, Wayne S., Longyuan Yang, James B. Cotner, Thomas H. Johengen, and Peter J. Lavrentyev. 2001. Nitrogen Dynamics in Sandy Freshwater Sediments (Saginaw Bay, Lake Huron*) Journal of Great Lakes Research*, 27, no. 1: 84–97. https://doi.org/10.1016/S0380-1330(01)70624-7.

Gillooly, J.F., Brown, J.H., West, G.B., Savage, V.M. and Charnov, E.L., 2001. Effects of size and temperature on metabolic rate. *Science*, 293(5538), pp.2248-2251.

Grizzle, J.M. & C.J. Brunner. 2009. Infectious disease of freshwater mussels and other freshwater bivalve mollusks. *Reviews in Fisheries Science*, 17(4)425-467.

Haag, W. R. 2012. North American Freshwater Mussels: Natural History, Ecology, and Conservation. *Cambridge University Press*, Cambridge, New York.

Haag, W.R. and A. Rypel. 2011. Growth and longevity in freshwater mussels: evolutionary and conservation implications. *Biological Reviews*, 86: 225-247. doi:10.1111/j.1469-185X.2010.00146.x

Haag, W.R., Culp, J., Drayer, A., McGregor, M.A., White, D.E.J., Price, S.J. 2021. Abundance of an Invasive Bivalve, Corbicula Fluminea, Is Negatively Related to Growth of Freshwater Mussels in the Wild. *Freshwater Biology* 66, no. 3: 447–57. https://doi.org/10.1111/fwb.13651.

Hawkins, A. J. S. , B. L. Bayne, A. J. Day and E. J. Denton. 1986. Protein turnover, physiological energetics and heterozygosity in the blue mussel, Mytilus edulis: the basis of variable age-specific growth. Proc. Royal Soc. B: 229: 161–176. http://doi.org/10.1098/rspb.1986.0080

Henley, W. F., Beaty, B.B., Jones, J.W. 2019. Evaluations of Organ Tissues from Actinonaias Pectorosa Collected During a Mussel Die-Off in 2016 at Kyles Ford, Clinch River, Tennessee. *Journal of Shellfish Research* 38, no. 3: 681–96. https://doi.org/10.2983/035.038.0320.

Hoellein, T., C. Zarnoch, D. Bruesewitz, and J. DeMartini. 2017. Contributions of Freshwater Mussels (Unionidae) to Nutrient Cycling in an Urban River: Filtration, Recycling, Storage, and Removal. *Biogeochemistry* 135, no. 3: 307–24. https://doi.org/10.1007/s10533-017-0376-z.

Hornbach, D. J., M. C. Hove, H.-T. Liu, F. R. Schenck, D. Rubin, and B. J. Sansom. 2014. The influence of two differently sized dams on mussel assemblages and growth. *Hydrobiologia*, 724:279-291.

Jones, J. W., E. M. Hallerman, and R. J. Neves. 2006. Genetic management guidelines for captive propagation of freshwater mussels (Uniodidae). Journal of Shellfish Research 25:527-535.

Jones, J., Lane, T., Ostby, B., Beaty, B., Ahlstedt, S., Butler, R., & Walker, C. 2018. Collapse of the Pendleton Island mussel fauna in the Clinch River, Virginia: setting baseline conditions to guide recovery and restoration. *Freshwater Mollusk Biology and Conservation*, *21*(2), 36-56.

Jones, M.P., Berg, D.J, Strenth, N.E. and Howells, R.G. 2018. Morphological Analysis of The Rio Grande Monkeyface, Quadrula Couchiana (Mollusca : Bivalvia) Using Photogrammetry.

Kellogg, L., J.C. Cornwell, M.S. Owens, and K.T. Paynter. 2013. Denitrification and Nutrient Assimilation on a Restored Oyster Reef. *Marine Ecology Progress,* Series 480 (April 22, 2013): 1–19. https://doi.org/10.3354/meps10331.

Kreeger, D. A. 1993. Seasonal patterns in the utilization of dietary protein by the mussel, *Mytilus trossulus*. Mar. Ecol. Prog. Ser. 95:215–232.

Kreeger, D. A., A. J. S. Hawkins, B. L. Bayne & D. L. Lowe. 1995. Seasonal variation in the relative utilization of dietary carbohydrate, protein-carbon and protein-nitrogen by Mytilus edulis (L.). *Mar. Ecol. Prog. Ser.* 126:177–184.

Kreeger, D.A. 2011. Physiological processing of suspended matter by freshwater mussels in rivers of Eastern Oregon. Final Report for the Confederated Tribes of the Umatilla Indian Reservation. 133 p. https://www.delawareestuary.org/science-and-research/freshwater-mussels/freshwater-mussels-news-reports/

Kreeger, D.A., P. Cole, M. Mills, L. Butler, A. Padeletti, R. Thomas, J. D'Agostino. 2013. Connecting people to aquatic biodiversity: freshwater mussel surveys in Pennsylvania's coastal zone. Partnership for the Delaware Estuary final report to the Pennsylvania Coastal Management Program. *PDE Report* No. 13-02. 65 p.

Kreeger, D.A., Gatenby, C., Bergstrom, P. 2018. Restoration Potential of Several Native Species of Bivalve Molluscs for Water Quality Improvement in Mid-Atlantic Watersheds. *Journal of Shellfish Research* 37, no. 5: 1121–57. https://doi.org/10.2983/035.037.0524.

Layzer, J. B., M. E. Gordon, and R. M. Anderson. 1993. Mussels: The forgotten fauna of regulated rivers - A case study of the Caney Fork River. *Regulated Rivers: Research and Management* 8:63-71.

Lopez, J. W., Parr, T. B., Allen, D. C., and Vaughn, C. C.. 2020. Animal aggregations promote emergent aquatic plant production at the aquatic–terrestrial interface. *Ecology*, 101(10):e03126. 10.1002/ecy.3126

Lunstrum, A., McGlathery, K., & Smyth, A. 2018. Oyster (Crassostrea virginica) aquaculture shifts sediment nitrogen processes toward mineralization over denitrification. *Estuaries and Coasts*, 41(4), 1130-1146.

McGonigal, K. H. 2006. Nutrients and suspended sediment transported in the Susquehanna River Basin, 2005, and trends, January 1985 through December 2005. *Technical Report* 248, Susquehanna River Basin Commission.

McMurray SE, Roe KJ. 2017. Perspectives on the controlled propagation, augmentation, and reintroduction of freshwater mussels (Mollusca: Bivalvia: Unionoida). *Freshwater Mollusk Biology and Conservation* 20: 1-12

Millennium Ecosystem Assessment. 2003. Ecosystems and human well-being: a framework for assessment. *Island Press*, Washington, DC.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. *Island Press*, Washington, DC

Moore, T. P., K. J. Collier, and I. C. Duggan. 2019. Interactions between Unionida and non-native species: A global meta-analysis. Aquatic Conservation: *Marine and Freshwater Ecosystems,* 29:1438-1451.

Newton, T. J., D. A. Woolnough, and D. L. Strayer. 2008. Using landscape ecology to understand and manage freshwater mussel populations. *Journal of the North American Benthological Society*, 27:424-439.

Nickerson, Z.L., B. Mortazavi, and C.L. Atkinson. 2019. Using Functional Traits to Assess the Influence of Burrowing Bivalves on Nitrogen-Removal in Streams. *Biogeochemistry* 146, no. 2: 125–43. https://doi.org/10.1007/s10533-019-00612-2.

Nirappil, F. 2019, October 23. Can tens of thousands of mussels help save the polluted Anacostia River?. *The Washington Post.*

Nobles, T. and Zhang, Y. 2011. Biodiversity Loss in Freshwater Mussels: Importance, Threats, and Solutions. Biodiversity Loss in a Changing Planet. *IntechOpen*. https://doi.org/10.5772/25102.

Ortmann, A.E. 1919. A monograph of the naiads of Pennsylvania. *Memoirs of the Carnegie Museum* 8:xvi-384

Pandolfo, T.J., W.G. Cope, G.B. Young, J.W. Jones, D. Hua, and S.F. Lingenfelser. 2012. Acute Effects of Road Salts and Associated Cyanide Compounds on the Early Life Stages of the Unionid Mussel Villosa Iris. *Environmental Toxicology and Chemistry* 31, no. 8: 1801–6. https://doi.org/10.1002/etc.1876.

Randklev, C.R., Hart, M.A., Khan, J.M., Tsakiris, E.T., Robertson, C.R. 2019. Hydraulic Requirements of Freshwater Mussels (Unionidae) and a Conceptual Framework for How They Respond to High Flows. Ecosphere 10, no. 12. http://dx.doi.org.proxy.library.vcu.edu/10.1002/ecs2.2975.

Richard et al., 2020. Scientific Reports 10:14498 | https://doi.org/10.1038/s41598-020-71459-z "novel densovirus"

Richard, J. C., Leis, E., Dunn, C. D., Agbalog, R., Waller, D., Knowles, S., Putnam, J., Goldberg, T. L. 2020. Mass mortality in freshwater mussels (Actinonaias pectorosa) in the Clinch River, USA, linked to a novel densovirus. *Scientific reports (Nature Publisher Group)*, 10(1), 1-10.

Riisgard, H. U. 1988. Efficiency of particle retention and filtration rate in 6 species of Northeast American bivalves. *Marine Ecology*, Ser. 45:217–223.

Sansom, B. J., Bennett, S. J., Atkinson, J. F., & Vaughn, C. C. 2018. Long-term persistence of freshwater mussel beds in labile river channels. *Freshwater Biology*, 63(11), 1469–1481. https://doi.org/10.1111/fwb.13175

Sousa, R., Antunes, C. and Guilhermino, L.E.D.P.S., 2008. Ecology of the invasive Asian clam Corbicula fluminea (Müller, 1774) in aquatic ecosystems: an overview. *In Annales de Limnologie-International Journal of Limnology* (Vol. 44, No. 2, pp. 85-94). EDP Sciences.

Spooner, D., Vaughn, C.C. 2006. Context-Dependent Effects of Freshwater Mussels on Stream Benthic Communities. *Freshwater Biology*, 51, no. 6: 1016–24. https://doi.org/10.1111/j.1365-2427.2006.01547.x.

Sprugel, D.G. 1983. Correcting for bias in log-transformed allometric equations. *Ecology* 64: 209-210.

Starliper, C. E. 2009. Pathogens and diseases of freshwater mussels in the United States: studies on bacterial transmission and depuration. Pages 12-20 in *Bridging America and Russia with Shared Perspectives on Aquatic Animal Health. Proceedings of the Third Bilateral Conference between Russia and the United States.*

Strayer, D.L., 1993. Macrohabitats of freshwater mussels (Bivalvia: Unionacea) in streams of the northern Atlantic Slope. *Journal of the North American Benthological Society*, 12(3), pp.236-246.

Strayer, D.L., S. Claypool, and S. Sprague. 1997. Assessing unionid populations with quadrats and timed searches. Pages 163-169 *In*: K.S. Cummings, A.C. Buchanan, C.A. Mayer, and T.J. Naimo (eds). Conservation and management of freshwater mussels II. Initiatives for the future. *Upper Mississippi River Conservation Committee*.

Strayer, D. L. 1999. Effects of alien species on freshwater mollusks in North America. *Journal of the North American Benthological Society*, 18:74-98.

Strayer, D.L., and A.R. Fetterman. 1999. Changes in the distribution of freshwater mussels (Unionidae) in the upper Susquehanna River basin, 1955-1997. *American Midland Naturalist* 142: 328-339.

Strayer, D. L., N. F. Caraco, J. J. Cole, S. Findlay, and M. L. Pace. 1999. Transformation of freshwater ecosystems by bivalves. *BioScience*, 49:19-27.

Strayer, D. L., J. A. Downing, W. R. Haag, T. L. King, J. B. Layzer, T. J. Newton, and S. J. Nichols. 2004. Changing perspectives on pearly mussels, North America's most imperiled animals. *BioScience*, 54:429-439.

Strayer, D. L., Malcom, H. M. 2007. Shell decay rates of native and alien freshwater bivalves and implications for habitat engineering. *Freshwater Biology* 52: 1611–1617.

Strayer, D. L. 2008. Freshwater mussel ecology: A multifactor approach to distribution and abundance. *University of California Press*, Berkeley, CA.

Strayer, D. L. 2009. Twenty years of zebra mussels: lessons from the mollusk that made headlines. *Frontiers in Ecology and the Environment*, 7:135-141.

Strayer, D. L. 2014. Understanding how nutrient cycles and freshwater mussels (Unionoida) affect one another. *Hydrobiologia* 735:277-292. DOI: 10.1007/s10750-013-1461-5.

Strayer, D. L. 2017. What Are Freshwater Mussels Worth?. *Freshwater Mollusk Biology and Conservation* ,20, no. 2 (October 2017): 103–13. https://doi.org/10.31931/fmbc.v20i2.2017.103-113.

Strayer, D.L., and Malcom, H.M. 2018. Long-term responses of native bivalves (Unionidae and Sphaeriidae) to a dreissenid invasion. *Freshwater Science* 37: 697-711

Strayer, D.L., J. Geist, W.R. Haag, J.K. Jackson, and J.D. Newbold. 2019. Essay: Making the most of recent advances in freshwater mussel propagation and restoration. *Conservation Science and Practice* 1: e53, doi: 10.1111/csp2.53

Tennis, J. 2018, July 13. Visiting legislators put hands on future of Clinch River, see region's tourism opportunities. *Bristol Herald Courier.*

Turek, K.A., T.J. Hoellein. 2015. The Invasive Asian Clam (*Corbicula Fluminea*) Increases Sediment Denitrification and Ammonium Flux in 2 Streams in the Midwestern USA. *Freshwater Science* 34, no. 2: 472–84. https://doi.org/10.1086/680400.

U.S. Fish and Wildlife Service (USFWS), Virginia. 2017. Restoration Plan and Environmental Assessment for the DuPont Waynesboro- South River/South Fork Shenandoah River/Shenandoah River Site. https://www.fws.gov/northeast/virginiafield/pdf/contaminants/dupont_waynesboro/20170414_DuPont_Waynesboro_RPEA_FINAL_signatures.pdf

Vaughn, C. C., Taylor, C.M. 1999. Impoundments and the decline of freshwater mussels: a case study of an extinction gradient. *Conservation Biology*, 13:912-920.

Vaughn, C. C. 2018. Ecosystem Services Provided by Freshwater Mussels. Hydrobiologia 810, no. 1 (March 15, 2018): 15–27. https://doi.org/10.1007/s10750-017-3139-x.

Watters, G. T. 1996. Small dams as barriers to freshwater mussels (Bivalvia, Unionoida) and their hosts. *Biological Conservation*, 75:79-85.

Watters, G. T. 2000. Freshwater mussels and water quality: a review of the effects of hydrological and instream habitat alterations. *Proceedings of the First Freshwater Mollusk Conservation Society Symposium* 1999:261-274.

Welsh, D.T., E. G. Castadelli. 2004. Bacterial nitrification activity directly associated with isolated benthic marine animals. *Marine Biology*. 144, pages 1029–1037.

Westbrook, P., L. Heffner, and M.K. La Peyre. 2019. Measuring carbon and nitrogen bioassimilation, burial, and denitrification contributions of oyster reefs in Gulf coast estuaries. *Marine Biology* 166: 4.

Westbrook, P., Heffner, L., & La Peyre, M. K. 2019. Measuring carbon and nitrogen bioassimilation, burial, and denitrification contributions of oyster reefs in Gulf coast estuaries. *Marine Biology*, 166(1), 1-14.

Zhu, J., C. Zarnoch, J. S. Gosnell, M. Alldred, and T. Hoellein. 2019. Ribbed Mussels *Geukensia Demissa* Enhance Nitrogen-Removal Services but Not Plant Growth in Restored Eutrophic Salt Marshes. *Marine Ecology Progress*, Series 631: 67–80. https://doi.org/10.3354/meps13132.

Appendix A: Workshop Agenda

Chesapeake Bay Program's (CBP)
Scientific and Technical Advisory Committee (STAC)
Workshop
Incorporating Freshwater Mussels in the Chesapeake Partnership
March 5-6, 2020

Location: Chesapeake Bay Foundation Philip Merrill Center, Annapolis, MD
Canvasback Meeting Room
Workshop Webpage: https://www.chesapeake.org/stac/events/incorporating-freshwater-mussels-in-the-chesapeake-bay-partnership/

Thursday, March 5

****Exact Times Are Subject to Change****

8:30 am **Coffee & Light Breakfast and networking (Provided)**

9:00 am **Introduction—***Joe Wood, Chesapeake Bay Foundation*

9:15 am **A brief history of Mussels and Ecosystem Services—** *Dave Strayer, Cary Institute*

9:45 am **The versatility (or headache) of diversity: understanding the ecological functions provided by complex mussel communities—** *Carla Atkinson, University of Alabama*

10:15 am **Holistic Shellfish Restoration for Clean Water—** *Danielle Kreeger, Partnership for the Delaware Estuary*

10: 40 am **Q & A for panel**

10: 50 am *Break*

11:00 am **Bivalve BMP's - Adapting Proposed Tidal BMP's to Flowing Waters?—** *Jeff Cornwell, University of Maryland Center for Environmental Studies*

11:20 am **Principles of the national strategy on Mussels- What might Ches Bay Aspire to?—***Bob Anderson, USFWS*

11:45 am **Concurrent Breakout Groups (boxed lunches)** Groups should identify detailed next steps including who will do what, provide policy recommendations and indicate if further discussions are warranted on such recommendations. Groups will report out (15 minutes to present, 5 minutes of discussion) to the broader group for input.

Group 1: Who are the Mussels of the Bay Watershed? Developing an Inventory of Chesapeake Bay Species and Restoration Efforts and looking towards goals. [Room: *Bufflehead*]
Group 2: The influence of Freshwater Mussel upon water resources: Ecosystem Services, Bioindicators and other benefits [Room: *Canvasback*]
Group 3: The influence of Bay restoration (and water quality) upon freshwater mussels: BMPs, threats, and the need for guidance. [Room: *Merganser*]

2:30 pm **Synthesis of Breakout Discussions**
15 minutes of report-out followed by 5 minutes for discussion from each breakout group

3:30 pm **Group Discussion of Next Steps, Day 2 breakout sessions**

4:00 pm **Extending the Reach: Strategies for Expanding Mussel Restoration —** *Mary Gattis (Mary Gattis, LLC)* Participants will identify target audiences and key messages most likely to prompt additional mussel restoration activity. The information from this session will inform communication and engagement strategies to be further developed following the workshop.

4:30 pm **Networking / Brainstorming Happy Hour (Provided by CBF) Sign up for Day 2 activities; Shell Identification Activities.**

5:00 pm **Casual Dinner**

<u>**Friday, March 6**</u>

8:00 am **Light Breakfast and Coffee (Provided)**

8:15 am **Recap of Day 1 and Setting the Stage for Day 2—***Joe Wood (CBF)* Discussion to review the findings from Day 1 discussions and set the charge for Day 2 in identifying concrete recommendations.

8:30 am **State and Federal Mussel efforts: Hatchery Work, Capacity and Mission- quick talks and panel**

Rachel Mair, USFWS, Julie Devers, USFWS, Danielle Kreeger, PDE, Brian Watson, DGIF, Jenny Landry, NYDEP, Amy Maher, NYDEP, Matt Ashton, MDE

9:15 am **Remediation framework consider mussels and their benefits?** — *Simeon Hahn, NOAA*

9:30 **Next steps, Instructions for Breakout sessions –** *Joe Wood (CBF)*

9:45 am **Concurrent Breakout groups (self-selected) Developing Specific Recommendations from small groups and further deliberations.** Participants will self-select into breakout groups to focus on developing specific recommendations and next-steps. Each group should prepare 2-3 slides to synthesize their findings.

Expected workgroups needed (Identify facilitators)

1. BMP expert panel recommendations (Merganser)
2. What kind of tools can we create or utilize to improve mussel outcomes? *Shawn McLaughlin*
3. What Mussel Goals should we set for the Chesapeake Bay Drainage?
4. Establishing a plan to ensure mussel populations are protected by Water quality Standards
5. BMP guidance for mussels: Stream Restoration, Ag, others?
6. Strategies to improve engagement and communication, *Mary Gattis?*
7. NRDA Workgroup (Terrapin) *Simeon Hahn*
8. Summarizing non-nutrient ecosystem services

11:15 am **Synthesize Results from Breakout Group Discussions→ Into Lunch,** Each breakout group will present their findings and open the floor for discussion on final recommendations and next-steps.

12:00 pm **Lunch (Provided)**

1:00 pm **Adjournment**

Appendix B: Workshop Participants

Last Name	First Name	Affiliation	Email
Mahar	Amy	New York Department of Environmental Conservation	ammahar@gw.dec.state.ny.us
Harvey	Annabelle	CRC, STAC Coordinator	harveya@chesapeake.org
Patil	Apurva	DOEE	apurva.patil@dc.gov
Johnston	Barbara	MD DNR	Barbara.Johnston2@maryland.gov
Anderson	Bob	PA FWS	Robert_M_Anderson@fws.gov
Watson	Brian	VA Dept of Wildlife Resources	Brian.Watson@dgif.virginia.gov
Atkinson	Carla	University of Alabama	Carla.l.atkinson@ua.edu
Sevcik	Clare	DNREC	Clare.sevcik@delaware.gov
Spooner	Dan	Hood College (USGS)	Dspooner45@gmail.com
Kreeger	Danielle	Partnership for the Delaware Estuary (PDE)	dkreeger@delawareestuary.org
Strayer	Dave	Cary Institute of Ecosystem Studies	strayerd@caryinstitute.org
Newbold	Dennis	Stroud Water Resources Center	newbold@stroudcenter.org
Myers	Doug	CBF Scientist	dmyers@cbf.org
Pickney	Fred	USFWS	Fred_pickney@fws.gov
Shenk	Gary	USGS (CBPO)	gshenk@chesapeakebay.net
Galbraith	Heather	USGS	hgalbraith@usgs.gov
Martin	James	VADEQ	James.martin@deq.virginia.gov
Vonesh	James	VCU, Community Ecologist	jrvonesh@vcu.edu
Keppler	Jason	Ag Chair (MDA)	jason.keppler@maryland.gov
Cornwell	Jeff	UMCES	cornwell@umces.edu
Greiner	Jennifer	FWS	jennifer_greiner@fws.gov
Van Houten	Jennifer	WSSL	jvanhouten@wetlands.com
Jones	Jess	FWS	jess_jones@fws.gov
Bible	Jillian	Washington College	jbible2@washcoll.edu
Wood	Joe	CBF; Workshop Chair	jwood@CBF.org
Jackson	John	Stroud Water Resources Center	jkjackson@stroudcenter.org

Pfeiffer	John	Smithsonian Museum of Natural History	PfeifferJ@si.edu
Montero	Jorge	Anacostia Watershed Society	jmontero@anacostiaws.org
Devers	Julie	USFWS	julie_devers@fws.gov
Ombalski	Katie	NFWF	katie@woodswaters.com
Linker	Lew	EPA, CBP	Linker.Lewis@epa.gov
Kellogg	Lisa	VIMS	lkellogg@vims.edu
Rosman	Lisa	NOAA	lisa.rosman@noaa.gov
Ronston	Liz	CBF	ERonston@cbf.org
King	Marel	CBC	mking@chesbay.us
Gattis	Mary	Mary Gattis, LLC	marygattisllc@gmail.com
Walsh	Mary	PA Conservancy	mwalsh@paconserve.org
Ashton	Matt	MD DNR	matthew.ashton@maryland.gov
Pennington	Matt	Local Leadership workgroup	mpennington@region9wv.com
Robinson	Matt	DOEE	matthew.robinson@dc.gov
Gray	Matthew	UMCES	mgray@umces.edu
Cole	Meg	CRC, STAC Staff	colem@chesapeake.org
Slattery	Michael	FWS	michael_slattery@fws.gov
Camp	Mieko	MDE-Conowingo	mieko.camp@maryland.gov
Selckman	Mike	ICPRB	Gmselckmann@icprb.org
Nelson	David Moe	NOAA	david.moe.nelson@noaa.gov
Popoff	Nicholas	FWS	nicholas_popoff@fws.gov
Bukaveckas	Paul	VCU	pabukaveckas@vcu.edu
Mair	Rachel	FWS	Rachel_Mair@fws.gov
Mason	Rich	FWS	rich_mason@fws.gov
Kobell	Rona	Maryland Sea Grant	kobell@mdsg.umd.edu
McLaughlin	Shawn	NOAA	shawn.mclaughlin@noaa.gov
Hahn	Simeon	NOAA	simeon.hahn@noaa.gov
Lingenfelser	Susan	FWS	susan_lingenfelser@fws.gov
Skelley	Suzanne	NOAA	suzanne.skelley@noaa.gov
Robertson	Tish	VA DEQ	Tish.Robertson@deq.virginia.gov
Ihde	Tom	MSU, STAC	Thomas.ihde@morgan.edu
Schueler	Tom	Chesapeake Stormwater network	watershedguy@hotmail.com

Appendix C: Methods for Conversions

Assumptions about freshwater mussel abundance

The current and historic distribution and abundance of freshwater mussels throughout the Chesapeake Bay watershed, as described in Chapter 1, is not precisely defined although patterns of distribution are well documented (e.g. Ortmann, 1919). Despite the exact estimates presented in this report, it has been well established that mussels are naturally patchy in their distribution both throughout the watershed and within a mussel "bed". Because of this, the group used a range of mussel densities to estimate the gross impact of freshwater mussels on denitrification rates in the bay. A breakout group from the workshop assumed a density of 1 - 10 mussels m^{-2} to represent historic populations of mussels in the watershed, and a range of .01 to 1 mussels $m^{-2}$to represent current population estimates. These estimates were based upon various sources and are documented in chapter 2. Further extrapolations were made assuming mussel densities of localized beds upwards to 100 mussels m.$^{-2}$ These densities are intended to reflect dense mussel beds that may have occurred historically. The densest mussel beds within the watershed which we were able to document were ~25 individuals m^{-2}, although examples of beds at 100 m^{-2} do exist outside the watershed. The group focused on available estimates for all necessary parameters (denitrification rates, mussel density, etc) from peer review literature and did not consider whether this nitrogen removal pathway might be enhanced in the future by efforts to restore mussel beds. Mussel body size was estimated based off of Strayer's (2014) assumption of one gram of soft tissue per mussel, which he used in conjunction with his estimated range of pristine population density.

Denitrification rates

As a means of assessing the upper bounds of plausible nitrogen removal by freshwater mussel, we selected the highest of the denitrification enhancements obtained from the literature- (Table 2.1)-- 84.1 µg N h^{-1} g^{-1} dry mass of soft tissue as reported by Nickerson et al (2019). We used the lowest value, 4.8 ug N h-1 g-1 from Hoellein 2017, to estimate the lower bounds of nitrogen removal. Literature reported N removal rates were converted to aerial removal rates (based upon chamber size) per gram of mussel (based upon chamber density). In order to derive estimates of the magnitude of impact, subsequent conversions were made for temperature, nitrate concentration, and overall potential mussel habitat, as described below.

Adjustment to ambient nitrate concentration

For an estimate of ambient nitrate concentrations in the Chesapeake Bay watershed, we used data for the Susquehanna River (McGonigal 2006). We used 1.1 mg nitrate-N L^{-1},, the average of the concentration from monitoring stations at Towanda, PA (0.73 mg L^{-1}) and at Marietta, PA (1.42 mg L^{-1}) in 2005 (McGonigal 2006). The difference between these two values likely reflects the greater intensity of agricultural lower in the basin. The annual load of total nitrogen at Marietta in 2005 was 6.3×10^7 kg y^{-1} (McGonigal 2006). This value is, nearly the same as the long-run load reported by Zhang et al. (2016) of 6.5 x 10 kg y^{-1}, suggesting that the concentrations we used are relevant and applicable to the long run. Nitrate made up 83% of the annual total nitrogen load at Marietta and 63% at Towanda (McGonigal, 2006).

The denitrification enhancement experiments of Nickerson et al. (2019) were conducted at a nitrate concentration of 0.14 mg N L^{-1}, far below our average of 1.1 mg N L^{-1} for the Susquehanna River, while the other experiments (Table 2.1) were conducted at concentrations similar to or greater than 1.1 mg L^{-1}. The Lotic Intersite Nitrogen eXperiment (LINX) ^{15}N addition studies (Mullholland et al., 2008) showed that, independent of the presence or absence of mussels, riverine denitrification increases with nitrate concentration, and that an increase in nitrate concentration from 0.14 to 1.1 mg N L^{-1} would be expected to increase denitrification by a factor of 2.75. Turek and Hoellein (2015) provided evidence that nitrate concentration influences mussel-enhancement of denitrification as well. They compared enhancement by the non-native clam *Corbicula* at sites with very different nitrate concentrations (0.04 and 2.5 mg L^{-1}, respectively), finding 2.5-fold greater enhancement at the high-nitrate site. Though their concentration range exceeded the range found between Nickerson et al.'s 0.14 mg N L^{-1} and the Susquehanna River's 1.1 mg N L^{-1}, it is not surprising that the increase should be less than predicted by the LINX study because, as the studies cited above have found, much of the mussel-enhanced denitrification may be coupled to nitrification within the sediments rather than consuming nitrate from the overlying water. With these considerations we applied an upward adjustment factor of 2.5, to the results of Nickerson et al. (2019). The factor of 2.5 is likely an over-estimate both because of the large concentration range of Turek and Hoellein (2015), and because most of the Susquehanna basin is forested where nitrogen yields are low (Ator et al., 2011), with nitrate concentrations likely well below the 1.1 mg N L^{-1} that we used as a benchmark. No adjustments were made to the other rates listed in Table 2.1.

Adjustment to annual temperature regime

We adjusted the reported rates of mussel-enhanced denitrification (DNFm; Table 2.1), which were conducted at temperatures ranging from 20 to 27 °C, to reflect the annual thermal regime of the Susquehanna River. We used United States Geological Survey (USGS) data to find that the typical summer peak of mean daily temperature in the Susquehanna at Marietta is about 26 °C. Pine Creek, PA, a large Susquehanna River tributary, peaks at ~25 °C, and Young Woman's Creek; a forested USGS benchmark stream, peaks at ~17 °C. All streams show a winter minimum of about 2 °C. We created an annual thermal regime of monthly temperatures scaled linearly between 2 °C and 25 °C, to which we applied the metabolic scaling equation proposed by Gillooly et al (2001):

$$k = e^{\frac{E(T-T_0)}{k_B T T_0}},$$

where k is the adjustment factor, T is the inferred river temperature in Kelvin, T_0 is the temperature (Kelvin) at which the DNFm of a given mussel was measured, k_B is Boltzmann's constant (8.617×10^{-5} eV K^{-1}), and E is the activation energy of metabolism for which we used 0.6 eV, a typical value found in the literature. *Fusconaiea cerina,* for example, was studied at 25.8 °C (Nickerson et al., 2019) from which we obtained k=0.43 as an annual average applicable to the Susquehanna.

For estimates DNFm applicable to the Susquehanna River we multiplied each of the literature reported DNFm rates (per gram soft tissue) by the respective concentration and temperature adjustments. Then, for the "average" estimates, we computed the mean of these values. We converted to DNFm per individual by multiplying by 1 g $individual^{-1}$ (for the lower bound and average estimates) or 1.64 g $individual^{-1}$ (for the upper bound).

Potential mussel habitat

Our basin-wide estimates were based on the area of stream bed within the watershed that might represent habitat. Our assumed mussel densities of 0.01, 1, and 10 mussels m-2 were intended to apply to the entire area of stream- and river-bed within the Susquehanna basin, excluding streams too small to support mussels (Strayer and Fetterman 1999, Strayer 2014), which we interpreted to be first-order streams. Downing et al. (2012) estimated that streams of Strahler order 2 (mean width 1.8 m) or greater occupy 0.54% of the land area of the contiguous United States. This and other studies (e.g., Allan et al., 2019) have shown that estimates of streambed area coverage show relatively little regional variation. Therefore, we applied the estimate of 0.54% to the Susquehanna basin area of 70182 km2 to arrive at streambed area of 380 x 10^6 $m^{2,}$ which was used, together with the various assumed mussel density.

Uncertainty

The approach applied here, including the scaling includes many elements of uncertainty. We utilized the best readily available estimate, e.g., for temperature, nitrate concentration, streambed area, in cases where that estimate seemed a good approximation without undue impact on the result. However, both the target population density and the nitrate concentration adjustment factors, have a wide range of uncertainty and a large impact on the final estimate. In the case of the target population, we tried to use a realistic range of what might currently and historically existed, but this number which is critical to the overall effect is unknown. In the case of the nitrate adjustment factor, we used estimates from the high end of the plausible range, i.e., to yield an upper bound estimate for the potential role of mussels. Finally, it is important to acknowledge that there are numerous issues that could influence these numbers. For example, denitrification per individual could be density dependent whereby increased density yields lower denitrification per individual. As such, we urge caution with relying heavily up on these values and urge further study on this subject.

Appendix D: Mussel Work in the Chesapeake Bay