CORRECTED PROOF

Short Communication

Identifying research in support of the management and control of dreissenid mussels in the western United States

Timothy D. Counihan[1,*], Lisa DeBruyckere[2], Stephen M. Bollens[3], Stephen Phillips[4], Theresa Thom[5] and Barak Shemai[6]

[1]*U.S. Geological Survey, Western Fisheries Research Center, Columbia River Research Laboratory, Cook, WA 98605, USA*
[2]*Creative Resource Strategies, LLC, 6159 Rosemeadow Lane NE Salem, OR 97317, USA*
[3]*School of the Environment, Washington State University, 14204 NE Salmon Creek Avenue, Vancouver, WA, 98686-9600, USA*
[4]*WIT Manager, Pacific States Marine Fisheries Commission, 205 SE Spokane, Street, Suite 100, Portland, Oregon 97202, USA*
[5]*U.S. Fish and Wildlife Service – Fish and Aquatic Conservation, 911 NE 11th Avenue, Portland, OR 97232, USA*
[6]*U.S. Fish and Wildlife Service – Southwest Region Aquatic Invasive Species Coordinator Box 1306. Albuquerque, NM 87103, USA*

**Corresponding author*
ORCID: 0000-0003-4967-6514
E-mail: *tcounihan@usgs.gov*

Citation: Counihan TD, DeBruyckere L, Bollens SM, Phillips S, Thom T, Shemai B (2023) Identifying research in support of the management and control of dreissenid mussels in the western United States. *Management of Biological Invasions* 14 (in press)

Received: 14 September 2022
Accepted: 4 January 2023
Published: 27 February 2023

Handling editor: David Wong
Thematic editor: Mattew Barnes

Abstract

On February 9–10, 2022, the Pacific States Marine Fisheries Commission, U.S. Fish and Wildlife Service, U.S. Geological Survey, and Washington State University hosted a workshop to establish research priorities that support the implementation of action items listed in a current invasive species management plan, the Quagga and Zebra Mussel Action Plan (QZAP) 2.0, that are intended to limit the establishment and spread of quagga and zebra mussels in the western United States. The workshop focus was on developing research priorities for the thematic areas that are addressed in QZAP 2.0: 1) early detection monitoring, 2) prevention and containment, 3) control and management, and 4) rapid response. In addition, research priorities were developed for a fifth thematic area that addressed dreissenid mussel biology. Forty scientists participated in the two-day workshop. Prior to the workshop, participants were asked to review and rank research priorities that were established for a previous version of the QZAP and to offer suggestions on emerging research priorities. During the workshop, subject matter experts presented information describing current knowledge of research and information associated with the thematic areas of early detection monitoring, prevention and containment, rapid response, control and management, and biology in the context of strategies and actions listed in QZAP 2.0. The rankings of previous research priorities and suggestions of emerging priorities were then reviewed, and a revised list of research priorities was formed. The list of research priorities is presented by thematic area.

Key words: invasive species, quagga, zebra, early detection monitoring, prevention, control, rapid response

Introduction

Quagga (*Dreissena rostriformis bugensis* (Andrusov, 1897)) and zebra (*Dreissena polymorpha* (Pallas, 1771)) mussels (hereafter, collectively, dreissenid mussels) are both economically and ecologically damaging. Numerous studies have examined the economic costs of mitigating the effects of dreissenid mussel infestations that include a variety of deleterious

effects on industrial and municipal water delivery systems and hydroelectric facilities (MacIsaac 1996; Connelly et al. 2007; IEAB 2010, 2013; Prescott et al. 2013; Robinson et al. 2013). Recent studies examining the potential costs of a dreissenid mussel infestation have suggested that the economic costs will be significant. For example, costs of a dreissenid mussel invasion at Snake River hydroelectric dams were estimated to be in the hundreds of millions of dollars (IEAB 2010). The deleterious effects of dreissenid mussels on ecological function, native flora and fauna, and water quality have also been studied and reported in areas with known infestations (Roper et al. 1997; Higgins and Zanden 2010; Karatayev et al. 2015).

In response to the discovery of dreissenid mussels in the western United States in 2007 efforts to prevent further infestations increased (Counihan and Bollens 2017), the Quagga-Zebra Mussel Action Plan (QZAP) was developed to identify priority actions and research needed to limit the spread of these invasive mussels (WRP 2010), and a Dreissenid Mussel Research Priorities Workshop was conducted in 2015 to update research priorities listed in the QZAP (Sytsma et al. 2015). The original QZAP was updated in 2020 to accommodate dreissenid mussel management and research advancements (WRP 2020). To update the research priorities identified in Sytsma et al. (2015), the Pacific States Marine Fisheries Commission, U.S. Fish and Wildlife Service, U.S. Geological Survey, and Washington State University hosted the invitation-only Dreissenid Mussel Research Priorities Workshop on February 9–10, 2022, to establish research priorities to support strategies and action items detailed in QZAP 2.0 (WRP 2020).

Materials and methods

Subject matter experts from the United States were identified based on whether they had dreissenid mussel management responsibility in the geographic area and/or demonstrated expertise in the topical areas covered by QZAP 2.0. Forty scientists participated in the two-day workshop (Table 1). The research prioritization focused on the thematic areas that are detailed in the QZAP 2.0 (WRP 2020): 1) early-detection monitoring, 2) prevention and containment, 3) research for control and management, and 4) rapid response. In addition, a fifth thematic area that addressed dreissenid mussel biology was included because it was considered in the previous research prioritization (Sytsma et al. 2015) and is relevant to the other thematic areas.

Prior to the workshop, participants were asked to review and rank research priorities listed in Sytsma et al. (2015) and to offer suggestions on emerging research priorities. During the workshop, scientists with expertise in early detection monitoring, prevention and containment, rapid response, control and management, and dreissenid mussel biology presented information describing the state of our current knowledge of research and information in the thematic areas. The presentations were

Table 1. Participants to the Dreissenid Mussel Research Priorities workshop that was convened virtually on February 9–10, 2022. Subject matter experts who provided information on the that state of current knowledge in topical areas are denoted by superscripts.

Participant	Organization
Colleen Allen[4]	National Park Service
Jon Amberg[2]	U.S. Geological Survey
Martina Beck[3]	British Columbia Ministry of Environment and Climate Change Strategy
Rick Boatner	Oregon Dept. of Fish & Wildlife
Stephen Bollens	Washington State University
Thomas Boos	Tahoe Regional Planning Agency
Tim Counihan[5]	U.S. Geological Survey
Lisa DeBruyckere	Creative Resource Strategies, LLC
Catherine de Rivera	Portland State University
Robyn Draheim	Consultant
Kate Dukette	Arizona Game and Fish Department
Ashley Elgin	NOAA Great Lakes Environmental Research Laboratory
Leah Elwell	Invasive Species Action Network
Caren Goldberg	Washington State University
Reuben Keller	Loyola University Chicago
Robert McMahon[1]	The University of Texas at Arlington
Rich Miller	Portland State University
Christine Moffitt	Oregon Invasive Species Council/ Western Regional Panel
Lennah Mohar	Washington Dept. of Fish and Wildlife
Dan Molloy	Molloy & Associates, LLC
Nanette Nelson	Flathead Lake Biological Station, University of Montana
Nathan Owens[4]	Utah Division of Wildlife Resources
Yale Passamaneck[5]	Bureau of Reclamation
Sherri Pucherelli[5]	Bureau of Reclamation
Gretchen Rollwagen-Bollens	Washington State University
Cristina Sanders	Bureau of Land Management
Jesse Schultz	Washington Department of Fish and Wildlife
Adam Sepulveda[2]	US Geological Survey
Barak Shemai	U.S. Fish and Wildlife Service
James Snider	California Department of Fish and Wildlife
Kelly Stockton-Fiti	KASF Consulting
Mark Sytsma	Portland State University
Theresa Thom	U.S. Fish and Wildlife Service
Jolene Trujillo	U.S. Bureau of Reclamation
Richard Visser	WA Dept Fish and Wildlife
Diane Waller	U.S. Geological Survey
David Wong[1]	Massachusetts Department of Environmental Protection
Thomas Woolf	Montana Fish Wildlife & Parks
John Wullschleger[3]	National Park Service
Nicholas Zurfluh[4]	Idaho State Department of Agriculture

[1] "Biology" subject matter experts.
[2] "Early detection monitoring" subject matter experts.
[3] "Prevention and containment" subject matter experts.
[4] "Rapid response" subject matter experts.
[5] "Control and management" subject matter experts.

followed by work sessions in each thematic area. Workshop attendees defined criteria for the inclusion of priority research topics; attendees supported use of the following criteria for all five thematic areas: 1) the research will support QZAP 2.0 (WRP 2020); 2) the research will positively affect the management of dreissenid mussels in the western United States, and 3) the research will fill identified research or information needs or gaps.

The ranked priorities of Sytsma et al. (2015) were considered at the 2022 workshop. A new priority list was then developed by workshop participants

Table 2. Research priorities and associated management outcomes that support actions described in the "early detection monitoring" section of the Quagga and Zebra Mussel Action Plan 2.0 (WRP 2020).

Research priority	Management Outcome
What are the most cost-effective population monitoring methods and protocols for dreissenid adults, juveniles, and veligers?	Improved efficiency of early detection monitoring and prevention programs
How can we use modeling to direct monitoring within a waterbody (e.g., predictions of the transport and fate of veligers)?	Improved focus of early detection monitoring and prevention programs
What are the most cost-effective monitoring methods for detecting dreissenid mussels at low densities?	Improved efficiency of early detection monitoring and prevention programs
Are there monitoring protocols that should be standardized and universally implemented?	Promote learning and sharing through the development of common methods and protocols
How do we incorporate new methods and technologies into early detection monitoring programs?	Improved early detection monitoring and prevention programs
How can we optimize methods for traditional plankton tow sampling/analysis?	Improved efficiency of early detection monitoring and prevention programs
How do we incorporate eDNA monitoring-into structured decision making?	Informed management decisions about how to use eDNA in early detection monitoring programs
How do we combine early detection monitoring tools to implement the most cost-effective monitoring program?	Improved early detection monitoring and prevention programs
What is the probability of detection associated with monitoring methods intended to detect dreissenid mussels at low densities?	Improved early detection monitoring and prevention programs
What metrics can we use to compare the efficacy of different types of monitoring?	Improved early detection monitoring and prevention programs
How do we best establish standard reporting protocols for monitoring results, methods, QA/QC-procedures, across monitoring methods (e.g., microscopy, eDNA, etc.)?	Promote learning and sharing through the development of common methods and protocols

and subsequently reviewed and revised for clarity by the steering committee. Management outcomes were then assigned to each of the priorities. The lists were then sent to workshop participants for review. Comments and reviews from workshop participants were resolved and incorporated.

Results and discussion

Based on the information presented by the subject matter experts and a review of priorities listed in Sytsma et al. (2015), workshop participants composed a list of research priorities for the thematic areas (Tables 2–6).

Early detection monitoring

Early detection monitoring research priorities (Table 2) were focused on refining early detection monitoring programs. Research that improves methods and techniques used to detect larval, juvenile, and adult dreissenid mussels was emphasized. For example, several research priorities would provide information about how existing and new tools can be used and integrated to provide cost-effective and efficient approaches to early detection monitoring. Also, understanding how well monitoring methods detect dreissenid mussels at low densities was listed as a priority. Discussion focused on consistency and repeatability of sampling regimes and the need for rigorous monitoring designs that consider the detection probabilities associated with sampling methods.

Table 3. Research priorities and associated management outcomes that support actions described in the "prevention and containment" section of the Quagga and Zebra Mussel Action Plan 2.0 (WRP 2020).

Research priority	Management Outcome
What physical, chemical, and biological tools are available to decontaminate boats as they are launched into and retrieved out of water bodies to decrease risk of dreissenid mussel infestation?	Improved prevention and containment programs
What are the existing and emerging pathways of dreissenid mussel introduction?	Improved prevention and containment programs that adaptively incorporate new information
How do we identify high-risk dreissenid mussel introduction pathways (e.g., boat haulers)?	Improved focus of prevention and containment programs on high-risk pathways
What are the most effective tools for the containment of dreissenid mussel infested water bodies?	Improved efficiency of containment programs
How can decontamination techniques be aligned with boat manufacturing standards?	Improved prevention and containment programs
Can we develop tools for increasing the efficacy of decontamination of boats?	Improved prevention and containment programs
How can we best coordinate with industry to identify environmentally friendly chemicals for treatment of boat ballast tanks?	Reduced effects of decontamination procedures on non-target ecosystem components
How does dreissenid veliger residence time in ballast tanks affect the probability of introduction?	Improved focus of prevention and containment programs

Table 4. Research priorities and associated management outcomes that support actions described in the "rapid response" section of the Quagga and Zebra Mussel Action Plan 2.0 (WRP 2020).

Research priority	Management Outcome
Can we develop an interactive map that illustrates the jurisdictions associated with rapid response plans?	Promote information sharing and learning and improve efficiency of rapid response programs
How can we automate and expand watercraft data collection techniques during a rapid response event?	Improved efficiency of rapid response programs
Can we expand the use of structured decision-making processes and tools for individual waterbodies during rapid response exercises?	Improved and streamlined decision making in response to a new invasion
How can we develop general tools and processes to guide structured decision making in a rapid response framework?	Improved and streamlined decision making in response to a new invasion
How can we efficiently and effectively develop regional pools of equipment and resources that will likely be needed during a rapid response?	Improved efficiency and cost-effectiveness of rapid response programs
What research is needed to support the development and advancement of a decision tool or guidelines to determine what treatment may be most appropriate for varying rapid response situations?	Improved and streamlined decision making in response to a new invasion
How can we best incorporate Indigenous peoples' preferences/values in structured decision-making?	Improved decision-making process

Prevention and Containment

Prevention and containment research priorities (Table 3) were concentrated on improving prevention and containment programs. Research intended to refine knowledge about the efficacy of decontamination methods were prevalent in the priorities listed. Priorities also included research to better understand introduction pathways, including new and emerging and high-risk pathways.

Rapid response

Rapid response research priorities (Table 4) emphasized the need to improve decision-making processes (e.g., structured decision making) associated with rapid response actions. In addition, research to improve data management

Table 5. Research priorities and associated management outcomes that support actions described in the "control and management" section of the Quagga and Zebra Mussel Action Plan 2.0 (WRP 2020).

Research priority	Management Outcomes
What are the acute and chronic effects of control options on non-target species, especially Endangered Species Act listed species and critical habitats?	Reduced effects of decontamination procedures on non-target ecosystem components
How do we measure the success of eradication and containment efforts (e.g., validation of control success)?	Improved decisions about management of control programs
What are the optimal timing windows for control options (e.g., reproductive cycle, time since infestation)?	Improved control programs
How can synthetic biocontrols, chemicals, and species-specific control technologies and techniques be used to control or eradicate, dreissenid mussels?	Improved control programs
What regulatory requirements and authorities need to be addressed to implement controls (e.g., chemicals, genetic biocontrols)?	Streamlined enactment of control measures
How can managers best evaluate tradeoffs when determining control options?	Improved decision making for control programs
What host-specific "novel" parasites, or other biocontrol agents, can be developed for dreissenid mussel control?	Improved control programs
How do we assess the effectiveness and new methods of controlling mussel populations in site-specific areas (e.g., infrastructure, boats, critical habitat, large water bodies)?	Improved control programs
How do we address gaps in our understanding of factors used to assess invasion risk?	Improved early detection monitoring and prevention strategies through a refinement of understanding of invasion risk
How can we best integrate existing and new data into predictive models that incorporate factors, such as traffic patterns and transportation pathways, to identify high-risk conveyances and high-risk water bodies to prioritize prevention and containment efforts?	Improved early detection monitoring and prevention strategies through a refinement of understanding of invasion risk
How can we establish metadata standards for data derived from rapid response and control efforts to improve future response efforts?	Promote and streamline information sharing and learning and improve efficiency of control and management efforts

and program efficiencies (e.g., promoting equipment sharing) and to better understand how to incorporate Indigenous peoples' values into rapid response decision making processes were listed as priorities. The development of tools that would clarify the geographic extent and authorities of existing rapid response plans was also identified as being important.

Control and management

Control and management research priorities focused on improving dreissenid mussel control programs (Table 5). Research priorities included measures to improve control methods and better understand the effects of control measures on non-target organisms. Because dreissenid mussel invasion risk assessment is included in the "control and management" section of QZAP 2.0 (WRP 2020), priorities included research to improve early detection monitoring and prevention programs by developing a better understanding of how habitat characteristics and introduction vectors affect invasion risk.

Biology

Biological research priorities (Table 6) were focused on informing and refining control and prevention strategies. For example, research that provides

Table 6. Dreissenid mussel biology research priorities and associated management outcomes that support actions in the Quagga and Zebra Mussel Action Plan 2.0 (WRP 2020).

Research priority	Management Outcome
What biotic and abiotic conditions limit the distribution, growth, and fecundity of dreissenid mussels?	Refinement of monitoring and prevention activities
What are the physiological tolerances of dreissenid mussels and are they adapting to changes in their environment?	Determine if invasion risk and risk assessments that incorporate physiological tolerances will change over time
How will dreissenid mussels affect the Columbia River system if climate change model predictions of future water temperatures and flows are the "new normal" in 25–50 years?	Inform strategies to mitigate the combined effects of climate change and a dreissenid mussel invasion and identify actions to promote resilience
What are the ecological effects of dreissenid mussels in the western United States?	Inform strategies to mitigate the effects of a dreissenid mussel invasion and identify actions to promote resilience
How can genomic research for dreissenid mussels be used in invasive mussel management?	Identify potential control strategies
Are there factors other than the typically evaluated water quality-based tolerances (e.g., calcium, pH, salinity, water temperature, etc.) that influence the survival of dreissenid mussels?	Refinement of risk assessments through a better understanding of factors affecting habitat suitability
What factors affect the probability of successful establishment of dreissenid mussels once veligers are introduced into a system?	Improved early detection monitoring and prevention strategies through a refinement of understanding of invasion risk

information that can be used to focus prevention actions (e.g., understanding what waterbodies are most likely to become infested and support populations of dreissenid mussels), was a priority. However, understanding how dreissenid mussels affect western aquatic ecosystems was also identified as a priority. Data gaps for basic water quality data including water temperature, pH, conductivity, and calcium concentrations were suggested as factors affecting a more thorough understanding of the effects of water quality on the establishment of dreissenid mussels.

Conclusions

The workshop results described here will help funding agencies identify research that will support action items in the QZAP 2.0 (WRP 2020). Some research topics spanned thematic areas. For example, research to improve decision making was included in the "early detection monitoring," "rapid response," and "control and management" thematic areas. Similarly, research to improve early detection monitoring (e.g., by refining understanding factors that affect invasion risk) was listed as a priority in the "biology," "early detection monitoring," and "control and management" thematic areas. Across all thematic areas, the research topics listed as priorities addressed a mix of control and prevention measures, but in general, were more focused on preventing dreissenid mussel infestations, reflecting the fact that many areas in the western United States are yet to be infested. There was some overlap between the research priorities identified in 2022 and 2015. For example, four of seven biological and four of eleven control and management research priorities were also identified in 2015, suggesting that some topics remain understudied.

Acknowledgements

We thank the participants of the workshop for their input and contributions to this work. We also sincerely thank the subject matter experts that presented information at the workshop for their contributions. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Funding declaration

Funding for this work was provided by the U.S. Fish and Wildlife Service (agreement #FIN0001603). TDC and LD received funds for this work from agreement # FIN0001603. Staff from the U.S. Fish and Wildlife Service were members of the workshop steering committee and provided input on the structure of the workshop, provided reviews of draft versions of this manuscript, and participated in the decision to submit this manuscript for publication.

Authors' contribution

TDC: workshop design and methodology; writing – original draft; writing – review and editing; LD: workshop design and methodology; writing – original draft; writing – review and editing; SMB: workshop design and methodology; writing – review and editing; SP: workshop design and methodology; writing – review and editing; TT: workshop design and methodology; writing – review and editing; BS: writing – review and editing.

References

Connelly NA, O'Neill Jr CR, Knuth BA, Brown TL (2007) Economic impacts of zebra mussels on drinking water treatment and electric power generation facilities. *Environmental Management* 40: 105–112, https://doi.org/10.1007/s00267-006-0296-5

Counihan TD, Bollens SM (2017) Early detection monitoring for larval dreissenid mussels: how much plankton sampling is enough? *Environmental Monitoring and Assessment* 189: 1–14, https://doi.org/10.1007/s10661-016-5737-x

Higgins SN, Zanden MV (2010) What a difference a species makes: a meta-analysis of dreissenid mussel impacts on freshwater ecosystems. *Ecological Monographs* 80: 179–196, https://doi.org/10.1890/09-1249.1

IEAB (2010) Independent Economic Analysis Board. Economic risk associated with the potential establishment of zebra and quagga mussels in the Columbia River basin. Task Number 159. Document IEAB 2010-1, 82 pp, https://www.nwcouncil.org/media/filer_public/ef/22/ef22358f-0a73-47e2-b320-8f14356d4020/ieab2010_1.pdf

IEAB (2013) Independent Economic Analysis Board. Invasive mussels update, Economic risk associated with the potential establishment of zebra and quagga mussels in the Columbia River basin. Task Number 201. Document IEAB 2013-2, 45 pp, https://www.nwcouncil.org/media/filer_public/9c/31/9c31503e-2420-423a-839e-9ff20473edba/ieab2013-2.pdf

Karatayev AY, Burlakova, LE, Padilla DK (2015) Zebra versus quagga mussels: a review of their spread, population dynamics, and ecosystem impacts. *Hydrobiologia* 746: 97–112, https://doi.org/10.1007/s10750-014-1901-x

MacIsaac HJ (1996) Potential abiotic and biotic impacts of zebra mussels on the inland waters of North America. *American Zoologist* 36: 287–299, https://doi.org/10.1093/icb/36.3.287

Prescott TH, Claudi R, Prescott KL (2013) Impact of dressenid mussels on the infrastructure of dams and hydroelectric power plants. In: Nalepa TF, Schlosser DW (eds), Quagga and zebra mussels: Biology, impacts, and control. Second Edition, CRC Press, Boca Raton, FL, pp 315–329

Robinson DCE., Knowler D, Kyobe D, de la Cueva Bueno P (2013) Preliminary damage estimates for selected invasive fauna in B.C. Report prepared for Ecosystems Branch, B.C. Ministry of Environment, Victoria, B.C. by ESSA Technologies Ltd., Vancouver, B.C., 62 pp, https://www2.gov.bc.ca/assets/gov/environment/plants-animals-and-ecosystems/invasive-species/publications/invasivefauna_economicimpacts_final_2013.pdf

Roper JM, Cherry DS, Simmers JW, Tatem HE (1997) Bioaccumulation of PAHs in the zebra mussel at times beach, Buffalo, New York. *Environmental Monitoring and Assessment* 46: 267–277, https://doi.org/10.1023/A:1005714318799

Sytsma MD, Phillips S, Counihan TD (2015) Dreissenid mussel research priorities workshop. Center for Lakes and Reservoirs Publications and Presentations. Paper 49, 23 pp. http://archives.pdx.edu/ds/psu/16500

WRP (2010) Western Regional Panel on Aquatic Nuisance Species. Quagga-Zebra mussel action plan for western waters. 45 pp, https://invasivemusselcollaborative.net/wp-content/uploads/2018/10/QZAP_FINAL_Feb2010.pdf

WRP (2020) Western Regional Panel on Aquatic Nuisance Species. Updated recommendations for the quagga and zebra mussel action plan for western U.S. waters. 32 pp, https://westernregionalpanel.org/wp-content/uploads/2020/12/QZAP-2.0-Final.pdf