Musseling out mussels: the status of MAISRC research on zebra mussel prevention and control

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MAISRC Showcase
Zebra mussels (*Dreissena polymorpha*)

Native range: southern Russia

**Invasive traits**

- **High fecundity**
  - Release eggs and sperm into water: 0.5 million eggs/female

- **Broad dispersal**
  - Veliger larvae develop 2-4 wks. in plankton, drifting long distances in lakes, down streams

- **Huge filtering capacity**
  - Attach with byssal threads to any firm surface (including other mussels)
  - Dense mussel beds remove $\frac{1}{2} - \frac{3}{4}$ plankton mass from lakes and rivers
North American invasion

- Several introductions to the Great Lakes in ship ballast water

- Appeared in Lake St Clair (1988: arrow)

- Through navigable waters (Great Lakes and Mississippi Basins, Hudson and Susquehanna Rivers)—they reached Louisiana to the south, Quebec and New York to the east, Oklahoma and Minnesota to the west in 5 years!

2011: Brown and Stepien
Spread to date in North America

- As of 2010
  - US and Canada*
    - 131 river systems
    - 772 inland lakes, reservoirs and impoundments
  - Minnesota as of December 2016**
    - 16 rivers and streams
    - 114 inland lakes

*From A. Benson (2014)
**From MN DNR AIS Program (K Pennington)
Minnesota’s rate of new inland invasions is now among the highest in the US

From Mallez and McCartney (in review)

We have the time, the will, and the resources to slow spread and prevent infestation of many prized water bodies!

• Prevention works, but must be targeted by
  • Understanding transport pathways to pinpoint invasion sources and routes, and vectors (boats, docks, lifts...)
    - Modeling boat traffic data
    - Genetics and genomics
1. Examine pathways of spread—where did mussels invading new lakes come from?—direct evidence from invasion genetics

2. Examine spread downstream through connected waterways

3. Examine the “residual water” vector of spread by watercraft
Invasion genetics at spatial scales useful to management...

Sophie Mallez, Michael McCartney (in review) *Biological Invasions*
Sampling zebra mussels

  - 69 sites - 44 water bodies – 2047 individuals
Mille Lacs Lake – a “hub” for other inland lakes?

• High boater traffic
• Infested early (2005)

Mille Lacs tested as a source for 35 lakes
Independent introductions scenario was selected in every case (with high probabilities, from 81% to 99%).

**Mille Lacs Lake: not the source for a single lake tested (35 lakes invaded post-2005)**
Take-home message

Boater movements: Mille Lacs (and Prior) Lakes have high traffic and are well connected, like “hubs,” to other lakes

Genetics: no detectable new infestations from these hubs

Bottom line: boat inspections/decontamination must be working and should be continued and expanded
The major pattern in MN: clustered invasions in lake-rich regions, due to:
1. Dispersal from outside region (red arrows) 2. Local spread (shaded colors)
Summary and management conclusions

• “Super-spreader” lakes: not infestation sources
  • High boater traffic, but genetics shows (so far) that they have not infested other lakes
  • Inspection/decontamination programs must be working (on Mille Lacs and Prior), should be continued and expanded

• Mussels spread locally in lake-rich regions
  • One or more original introductions from outside the region
  • After this—local spread (overland and downstream)
  • Vectors spreading mussels locally must be identified and blocked
Vectors of zebra mussel spread to inland lakes

• “Natural” spread through interconnected waterways
  – Downstream dispersal of veliger larvae or other life stages (e.g. rafting juveniles)

• Overland via recreational boating
  – Veligers in water (in hulls, live wells, etc.)
  – Mussels attached to vegetation (entangled on trailers, motors, etc.) or to docks, lifts, boat hulls
Stream connections greatly increase risk for invasion of MN lakes

<table>
<thead>
<tr>
<th>Infested</th>
<th>Not connected</th>
<th>Connected</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>12851</td>
<td>1742</td>
</tr>
<tr>
<td>Yes</td>
<td>391</td>
<td>604</td>
</tr>
<tr>
<td>% Infested</td>
<td>2.95</td>
<td>25.7</td>
</tr>
</tbody>
</table>

Lake connectivity and zebra mussel infestations in MN. Values in cells are numbers of comparisons (n > 15,500) between focal infested lakes [n = 91 (as of 2015)] and all other lakes located ≤ 30 km from the focal lakes. Lakes that are connected to focal infested lakes are infested with zebra mussels 8.7 times more frequently that lakes that are not connected to focal infested lakes. A G-test of independence shows that infested/not-infested status was highly dependent on whether lakes were connected: $G_{adj} = 1199.4, P < 0.001$. 
Downstream lakes are more likely invaded than upstream lakes

<table>
<thead>
<tr>
<th>Infested</th>
<th>Upstream</th>
<th>Downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>1663</td>
<td>79</td>
</tr>
<tr>
<td>Yes</td>
<td>451</td>
<td>153</td>
</tr>
<tr>
<td>% Infested</td>
<td>21.3</td>
<td>65.9</td>
</tr>
</tbody>
</table>

Location up or downstream of infested lakes influences the likelihood of infestation for connected lakes. Values in cells are numbers of comparisons between focal infested lakes and other connected lakes ≤ 30 m from the focal lakes (see text for details). For downstream connected lakes, the percent that are infested was found to be 3.1 times the percent of upstream connected lakes that are infested. G-test of independence: $G_{adj} = 187.06, P < 0.001.$
Map River/stream Study years
1 Gull River 2014
2 Pine River 2015
3 Minnehaha Creek 2015
4 Pelican River 2014, 2015
Downstream drift studies in Minnesota

- Samples, at increasing distances downstream from the infested lake, ending near the inlet:
  - **Settlement** of juvenile mussels; reproductive season (June-October)
  - **Veliger** concentrations (June-October); 150 L water pumped and 50-micron filtered
Bottom line for management

- In small streams (< 30 feet wide) settlement is limited to stream bottom just downstream of source lake
  - Adult populations will not establish on stream bottom far downstream
  - Limits threat e.g. to freshwater mussel populations
Bottom line for management

• Instead, streams are high-risk “conduits” for spread to downstream lakes by larvae

  – Millions to billions of larvae per day travel to lakes over short stream distances

  – Rapid decline with distance, but long distance transport occurs (e.g. Pelican, Pine River systems)
Bottom line: management

- Instead, streams are high-risk “conduits” for spread to downstream lakes by larvae

- Headwater lakes should be prioritized for prevention and treatment
• Residual water remains in boats after reasonable attempts to drain

• Water contains veliger larvae
  – How many?
  – Variation across vessel types, compartments
  – Survival upon arrival at next water body
1. Live wells and other recreational boat compartments:
   a. Low residual water volumes
   b. Veliger numbers are small

2. I/O engines and ballast tanks
   a. Higher volumes and veliger counts
   b. Veligers do not survive (in field samples)
3. Experimental live well chambers

a. Survival declines across realistic temperature range

b. >= 90% mortality after 6 hours
Sampling larvae pumped from Lake Minnetonka into a ballast bag  Adam Doll, Rosie Daniels

Photos by David Hansen
4. Experimental ballast bag samples

a. High variation in veliger counts and survival

b. A few samples contain moderate numbers of live veligers (hours after collection)
What can be done to control or eliminate zebra mussels?

• Mechanical controls
  – Hand harvest
  – Draw downs

• Biological control

• Chemical treatment
Zebra Mussels Removed from Lake George

<table>
<thead>
<tr>
<th>Site (year discovered)</th>
<th># Removed *</th>
</tr>
</thead>
<tbody>
<tr>
<td>LG Village (1999)</td>
<td>21,278</td>
</tr>
<tr>
<td>Cleverdale (2004)</td>
<td>1,380</td>
</tr>
<tr>
<td>Mossy Point (2004)</td>
<td>1,816</td>
</tr>
<tr>
<td>Sandy Bay (2006)</td>
<td>451</td>
</tr>
<tr>
<td>Rogers Rock (2007)</td>
<td>231</td>
</tr>
<tr>
<td>Yankee Marina (2007)</td>
<td>36</td>
</tr>
<tr>
<td>Castaway Marina (2007)</td>
<td>47</td>
</tr>
<tr>
<td>Treasure Cove (2008)</td>
<td>188</td>
</tr>
<tr>
<td>Beckley’s (2008)</td>
<td>22</td>
</tr>
<tr>
<td>Middle Bay (2009)</td>
<td>26</td>
</tr>
<tr>
<td>Total</td>
<td>25,475</td>
</tr>
</tbody>
</table>

* As of the end of 2009. Zebra mussels removed by divers from the Darrin Fresh Water Institute, Bateaux Below, and InnerSpace Scientific Diving.

For more info about zebra mussels or to learn more about the LGA & how to support its work, go to www.lakegeorgeassociation.org.
## Chemical treatments for zebra mussels in Minnesota

<table>
<thead>
<tr>
<th>Lake</th>
<th>County</th>
<th>Year treated</th>
<th>Agent(s)</th>
<th>Current Status</th>
</tr>
</thead>
</table>
| Minnewashta| Hennepin | 2016               | EarthTec QZ™ (copper sulfate formulation) | • No mussels found in treatment area after treatment  
• Status: evaluation in progress; follow up monitoring begins 2017 |
| Ruth       | Crow Wing| 2015               | EarthTec QZ™                          | • No mussels found in treatment area after treatment  
• No adults, larvae or settling juveniles found lake-wide through summer 2016  
• Fall 2016: one dead mussel found attached to a boat lift pulled from the lake  
• Status: uncertain |
| Christmas  | Hennepin | Fall and Winter 2014, Spring 2015 | EarthTec QZ™, potash (potassium chloride), Zequanox | • No mussels found in treatment area to date (2 years post-treatment)  
• Fall 2015: 16 mussels found on equipment from sites distant from treatment area  
• Sizes of these mussels suggests that reproduction occurred  
• Status: the lake population is now growing |
| Independence| Hennepin | Fall 2014, Spring 2015 | EarthTec QZ™, potash | • 49 mussels found in 2015 (one year after the first treatment)—in the treatment area  
• Follow-up survey in 2016—only 3 mussels found, no small animals, no reproduction  
• Status (tentative): population suppression |
| Rose       | Otter Tail| 2011               | Cutrine®-Ultra (liquid chelated copper algicide) | • Survey in spring 2012 found 3 mussels remaining within the treatment area  
• Surveys from 2013 through 2015: no mussels found, lake-wide  
• Status: successful population suppression, being monitored |
| Irene      | Douglas  | 2011               | Cutrine®-Ultra                        | • Like Rose Lake, Irene was infested by a boat lift, and treated using Cutrine Ultra  
• We are not aware of follow up information prior to Fall 2014  
• Status: population has grown and is widespread |
Strategies for chemical control

1. Research on chemical treatment of newly infested lakes

   a. Assisting in management efforts—new information on treatment methods, efficacy

   b. Developing monitoring protocols for trial lakes (MN DNR “Pilot Projects”)

Christmas Lake pesticide treatment trials, 2014-2015

Lessons learned: Lund et al. (in press)

Lake and Reservoir Management
c. MAISRC-funded research on SCUBA survey designs for mussels at low density (when they are treatable)

K Cattoor, MN DNR

Rensselaer Polytechnic Institute, Troy NY
c. MAISRC-funded research on SCUBA survey designs for mussels at low density (when they are treatable)

Quantitative ecology
John Fieberg, Co-PI
Jake Ferguson (Postdoctoral)

Zebra mussel biology/ecology
Michael McCartney, Co-PI

Field crew
Divers: Naomi Blinick (lead),
Leslie Schroeder.
Sarah Baker (field assistant)
2. Reducing populations by targeting larvae with low dose chemical treatments

Photos by David Hansen
• If higher sensitivity of larvae, in lab, is found with in-lake testing:
  – Larvae could be targeted with lower doses, larger treatment areas, fewer effects on native animals
  – Control of zebra mussel populations by reducing annual “settlement” of larvae may be feasible
Larval toxicity testing in an infested lake

We tested EarthTecQZ™ (a highly toxic zebra mussel pesticide) on larvae, in Lake Minnetonka

- Dose-response (2016): > 100 times more toxic to larvae (in-lake) than to adults (in-lab)

- Exposure time (2017): 100% of larvae removed from the water column in about 3 days at low dose (1/16th dose used in MN lake treatments)
Future prospects for control

• Once an infestation is established: few options

• We need population control agents that we can spread throughout an infested lake

• Genetic biocontrol technology is rapidly becoming an option
The Zebra Mussel Genome Project

• Sequencing the zebra mussel genome
  • 100s of millions of fragments of DNA sequence, some very short, others very long
  • Piled up and “stitched together” using bioinformatics
  • Describe and name zebra mussel genes that control important functions

• Searching the genome for target genes
  • Critical genes for development and reproduction
  • Genes controlling byssal thread attachment
  • Genes for shell formation (calcium threshold)

• Genetically edit target genes, insert into zebra mussels for eventual trial releases in lakes
Thanks: genetics and genomics

**MnDNR** Keegan Lund, Mark Ranweiler, Dan Swanson, Rich Rezanka and several others for help collecting

**USGS** Dr. Wendylee Stott, Dr. Mary Anne Evans **NOAA** Ashley Baldridge Elgin; **INHS** Jeremy Tiemann for collecting from lower Great Lakes

**McCartney Lab** Dr. Sophie Mallez, Melody Truong

**UMN Genomics Center** K Beckman, D Gohl, S Anderson, J Garbe, B Auch

**MN Supercomputing Institute** K Silverstein

**Funding:** Clean Water, Land and Legacy Fund (2014-2016); Environment and Natural Resources Trust Fund (current), MAISRC, Gull Chain of Lakes Association, Pelican Lakes Association.
Thanks: downstream spread

**UMN**  Grace Van Susteren, Sarah Peterson, Sendrea Best, Peter Xiong, Max Kleinhaus (field and lab assistants)

**RMB Labs**  Moriya Rufer for discharge data, help and advice in the Pelican River Watershed

**MnDNR**  Joshua Prososki for discharge data on the Pelican River

**USACE**  Corrine Hodapp for discharge data on the Pine River

**Funding**  Clean Water, Land and Legacy Fund, MAISRC, Gull Chain of Lakes Association, Pelican Lakes Association
Thanks: residual water

**MnDNR** Ann Pierce, Heidi Wolf, Adam Doll, Watercraft Inspection Program staff

**McCartney Lab** Adam Doll, Rosemary Daniels

**MAISRC** Becca Nash

**Brunswick FWBG**, New York Mills Plant for constructing experimental live well chambers (for free)

**Tonka Bay Marina** For sampling of I/O engines, ballasts and other logistical support

**Funding:** MAISRC, Tonka Bay Marina, Brunswick Freshwater Boat Group, MN DNR, Mr. Gabriel Jabbour
Thanks: chemical control projects

**UMN** Max Kleinhaus, Melody Truong, Sarah Baker, Sonia Ehrlich (field and lab assistants); Sophie Mallez

**Minnehaha Creek Watershed District** E Fieldseth, J Sweet

**BlueWater Science Consulting** Steve McComas; **Dan Molloy** for histological work; **PLM Lake & Land Management Corp.** Patrick Selter, for performing the molluscicide treatments; **Christmas Lake Homeowner’s Association** Joe Schneider (President), Christmas Lake residents, and the city of Shorewood for the Christmas Lake project

**Three Rivers Park District** B Vlach, A Smith for Minnetonka work

**MnDNR** Rich Rezanka, Marc Bacigalupi for SCUBA survey work, Keegan Lund, K Pennington, H Wolf and several others in the EWR program

**Funding** Hennepin County AIS Grants Program, MAISRC
Questions??

www.maisrc.umn.edu

Email: mmccartn@umn.edu
Analysis of genetic diversity

Broad pattern:
Lakes are colonized by large numbers of mussels
Brainerd Lakes: 1 unique genetic cluster (yellow shading) found nowhere else

Includes Cass and Winnibigoshish Lakes

* = Tested lake
ZM = Infested lake
Summary and management conclusions

• High genetic diversity: Infestations are founded by many individuals
  • If veligers in water moved by boats are the vector—multiple and/or massive introductions
  • Vectors that transport juveniles or adults—plants on trailered boats, docks, lifts, resident boats—seem more likely

• “Super-spreader” lakes: not infestation sources
  • High boater traffic, but genetics shows (so far) that they have not infested other lakes
  • Inspection/decontamination programs must be working (on Mille Lacs and Prior), should be continued and expanded

• Mussels spread locally in lake-rich regions
  • One or more original introductions from outside the region
  • After this—local spread (overland and downstream)
  • Vectors spreading mussels locally must be identified and blocked
Settlement in streams is highly localized near the upstream lake.
### Veliger transport to downstream water bodies

<table>
<thead>
<tr>
<th>River</th>
<th>Year</th>
<th>Month</th>
<th>Veligers/sec outlet</th>
<th>Veligers/sec inlet</th>
<th>% Decline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gull</td>
<td>2014</td>
<td>July</td>
<td>2866</td>
<td>290</td>
<td>89.9</td>
</tr>
<tr>
<td>Gull</td>
<td>2014</td>
<td>August</td>
<td>451</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Minnehaha</td>
<td>2015</td>
<td>June</td>
<td>216</td>
<td>20</td>
<td>90.7</td>
</tr>
<tr>
<td>Minnehaha</td>
<td>2015</td>
<td>July</td>
<td>383</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Minnehaha</td>
<td>2015</td>
<td>August</td>
<td>3320</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Pine</td>
<td>2015</td>
<td>June</td>
<td>25363</td>
<td>12038</td>
<td>52.5</td>
</tr>
<tr>
<td>Pine</td>
<td>2015</td>
<td>July</td>
<td>905</td>
<td>8</td>
<td>99.2</td>
</tr>
<tr>
<td>Pine</td>
<td>2015</td>
<td>August</td>
<td>2175</td>
<td>133</td>
<td>93.9</td>
</tr>
<tr>
<td>Pelican</td>
<td>2015</td>
<td>June</td>
<td>308123</td>
<td>11697</td>
<td>96.2</td>
</tr>
<tr>
<td>Pelican</td>
<td>2015</td>
<td>July</td>
<td>52799</td>
<td>14</td>
<td>99.9</td>
</tr>
<tr>
<td>Pelican</td>
<td>2015</td>
<td>August</td>
<td>1712</td>
<td>403</td>
<td>76.4</td>
</tr>
</tbody>
</table>

**Threat**
- High
- Moderate
- Zero
## Veliger transport to downstream water bodies

<table>
<thead>
<tr>
<th>River</th>
<th>Year</th>
<th>Month</th>
<th>km to threshold</th>
<th>km to inlet</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gull</td>
<td>2014</td>
<td>July</td>
<td>7.5</td>
<td>22</td>
<td>19.4</td>
</tr>
<tr>
<td>Gull</td>
<td>2014</td>
<td>August</td>
<td>56.2</td>
<td>22</td>
<td>97.0</td>
</tr>
<tr>
<td>Minnehaha</td>
<td>2015</td>
<td>June</td>
<td>8.7</td>
<td>32</td>
<td>12.1</td>
</tr>
<tr>
<td>Minnehaha</td>
<td>2015</td>
<td>July</td>
<td>4.8</td>
<td>32</td>
<td>11.3</td>
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<tr>
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<td>August</td>
<td>10.0</td>
<td>32</td>
<td>11.0</td>
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<tr>
<td>Pine</td>
<td>2015</td>
<td>June</td>
<td>563</td>
<td>29</td>
<td>788</td>
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<td>July</td>
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<td>215</td>
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<tr>
<td>Pine</td>
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<td>August</td>
<td>14.3</td>
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<td>June</td>
<td>78.0</td>
<td>64</td>
<td>90.5</td>
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<tr>
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<td>2015</td>
<td>July</td>
<td>51.7</td>
<td>64</td>
<td>66.7</td>
</tr>
<tr>
<td>Pelican</td>
<td>2015</td>
<td>August</td>
<td>—</td>
<td>64</td>
<td>—</td>
</tr>
</tbody>
</table>

### Threats

- **High**
- **Moderate**
- **Zero**

\[ 1 \text{2-parameter exponential} \]

\[ 2 \text{0.1 veliger/s or } 8.64 \times 10^3 \text{ per day} \]
Predators

Several native and non-native species eat zebra mussels, but none can control them in North America.
1. Research on chemical treatment of newly infested lakes.

   a. Assist in real-time management efforts, gather information on treatment methods.

   b. Develop monitoring protocols. Example: MN DNR Pilot Projects

   c. Develop designs for SCUBA survey of mussels in low density, new infestations.